The Interactions Between rf and Structure Parameters in High Gradient Systems

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ANL/HEP

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Neutrino Factory
Muon Collider

THE UNIVERSITY OF CHICAGO

Office of Science
U.S. DEPARTMENT OF ENERGY

Argonne
NATIONAL LABORATORY

Outline

- Motivation
- Our Approach
- Our Model of Cavity Operation
- Using the Model
- Conclusions

Motivation:

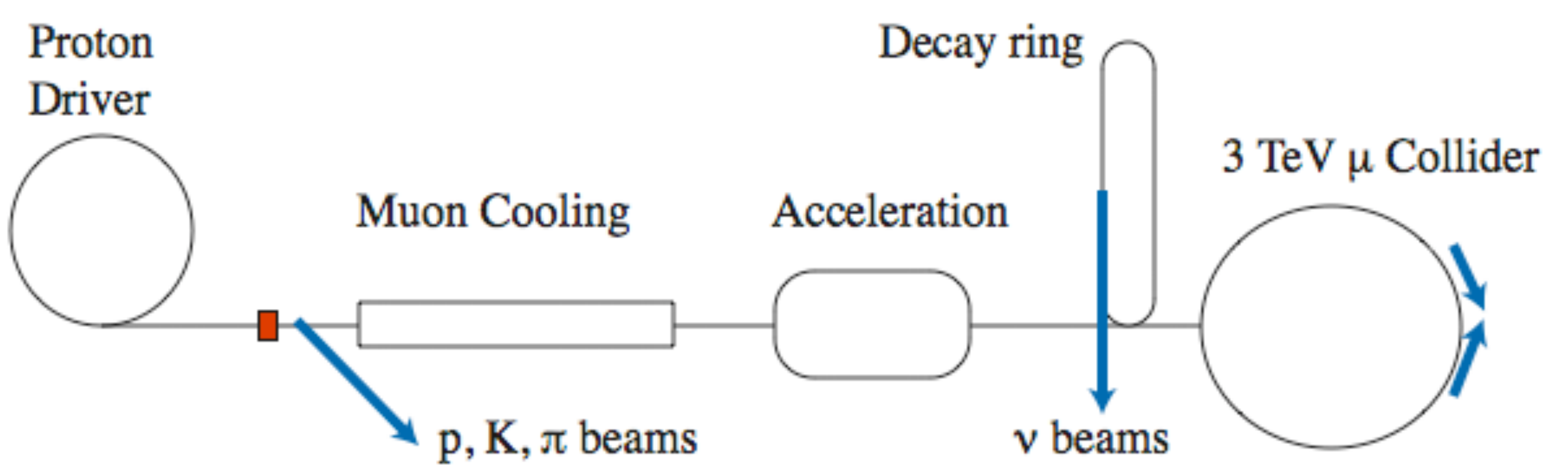
- If Muon Cooling works one will be able to build a facility for leptons that can:

  + Collide leptons at 3 times the energy of the ILC.

  + Produce neutrino beams of unprecedented intensity and purity.

  + Produce high intensity proton and low energy meson beams for HEP

  ➜ Access all HEP problems (3TeV$_{cm}$ Collider, neutrinos, mesons, protons)
  Supports a Fermilab scale facility for years.



.. . . and,

There are other general arguments for this work.

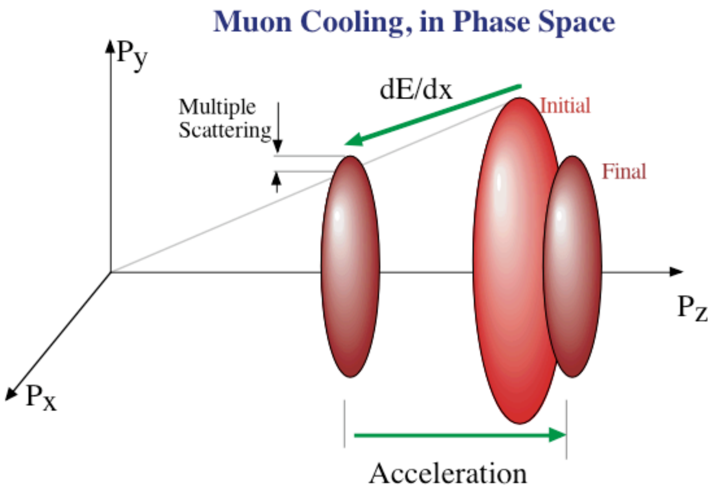
- We don't want the success of future accelerator projects to be compromised by inadequate knowledge of basic processes.

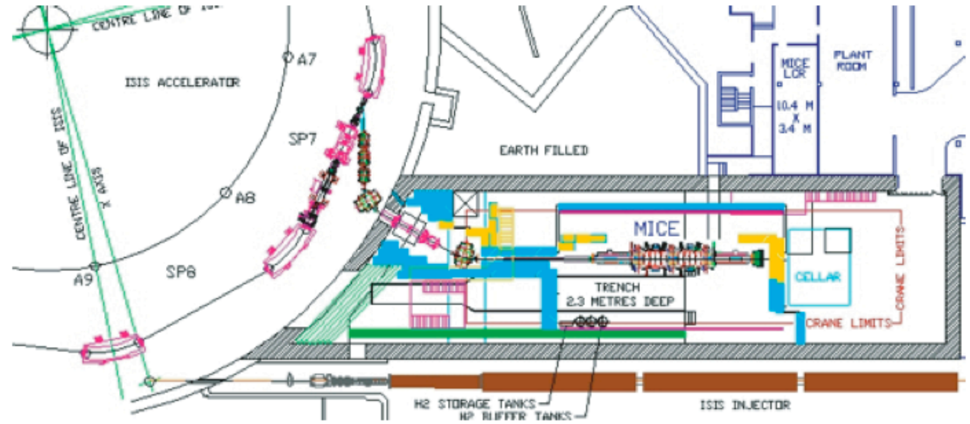
- Understanding of operational limits of basic technologies is very primitive.

- The increasing costs of facilities makes failures more expensive.

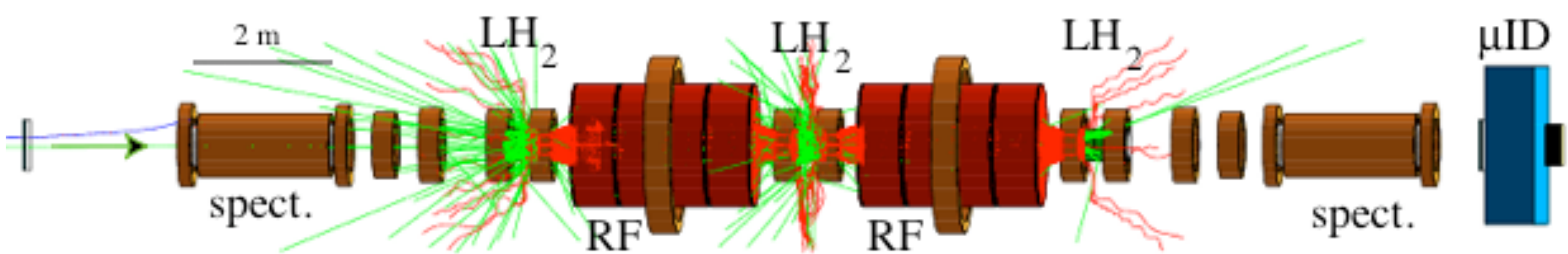
- Long study has shown that the parameter space for producing useful linear colliders is very small. Metal structures seem required to provide the beam stability and wall plug efficiency.

MuCool work is directed at MICE (at RAL).





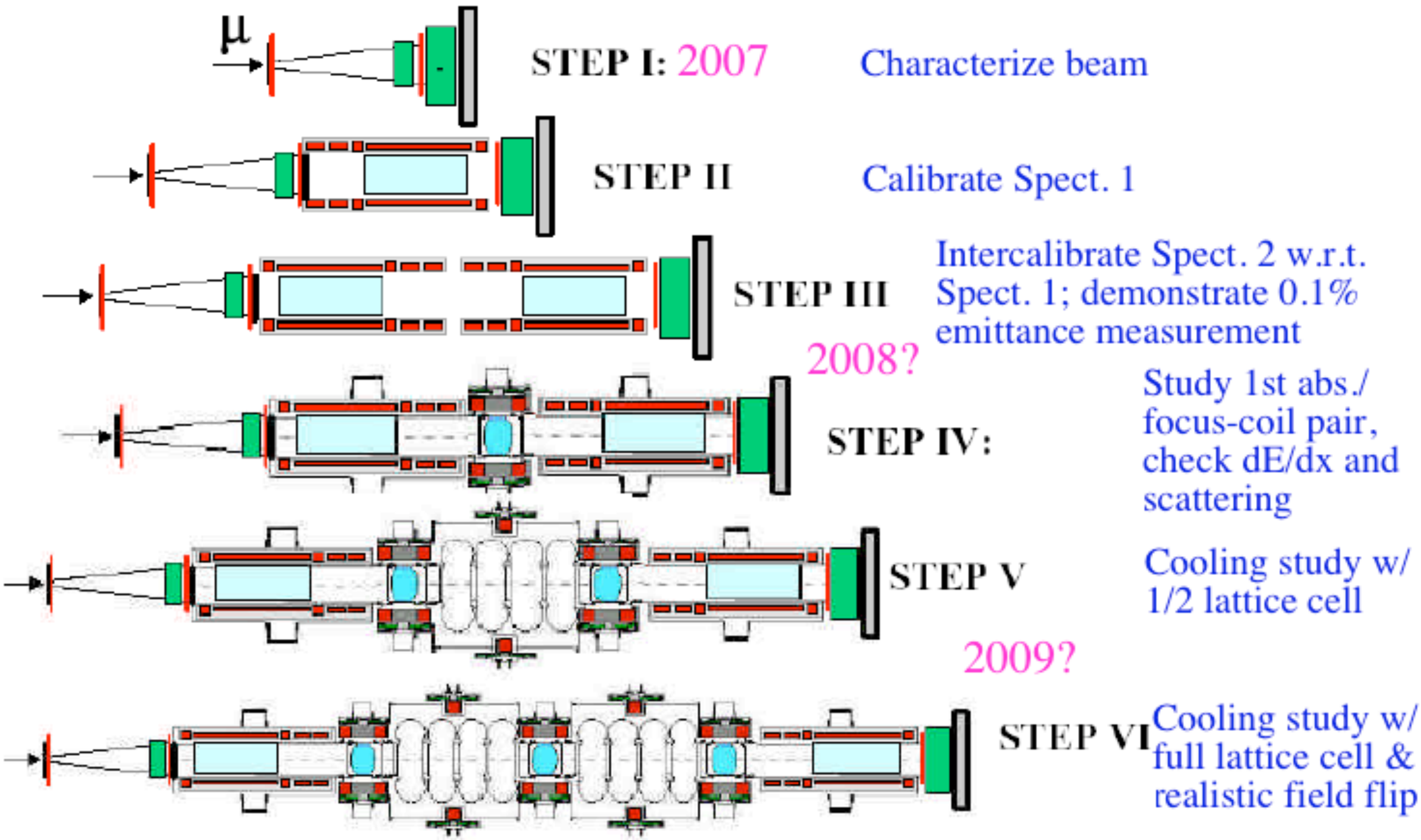
The Muon Ionization Cooling Experiment (MICE)



- Needs: 1) Reach full *E* field with 3 – 5 T solenoid.
  2) Reduce backgrounds in spectrometers.

We need to understand high gradients. Now.

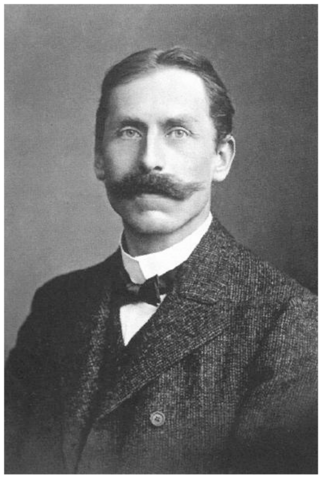
- MICE, and muon cooling, require high electric fields in high solenoidal fields.
- This physics/material science is not understood.



The Breakdown Problem is very old.

Many have contributed - very early:

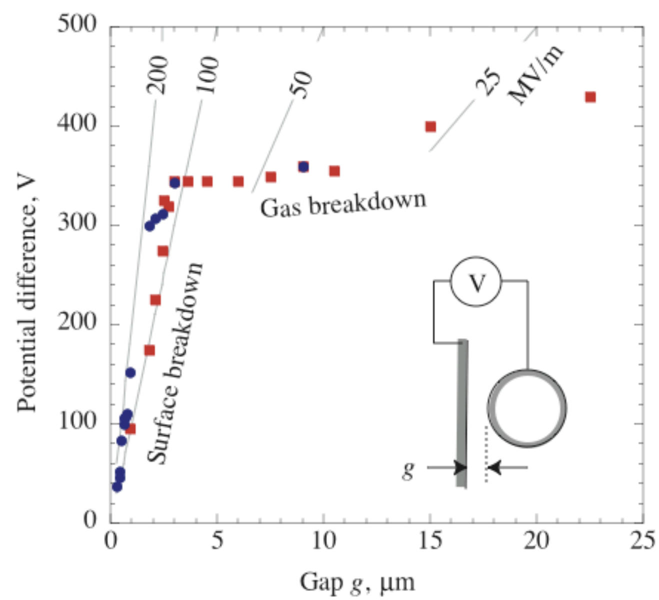
Paschen, Millikan Michelson, Lord Kelvin



In 1904, Lord Kelvin argued that:

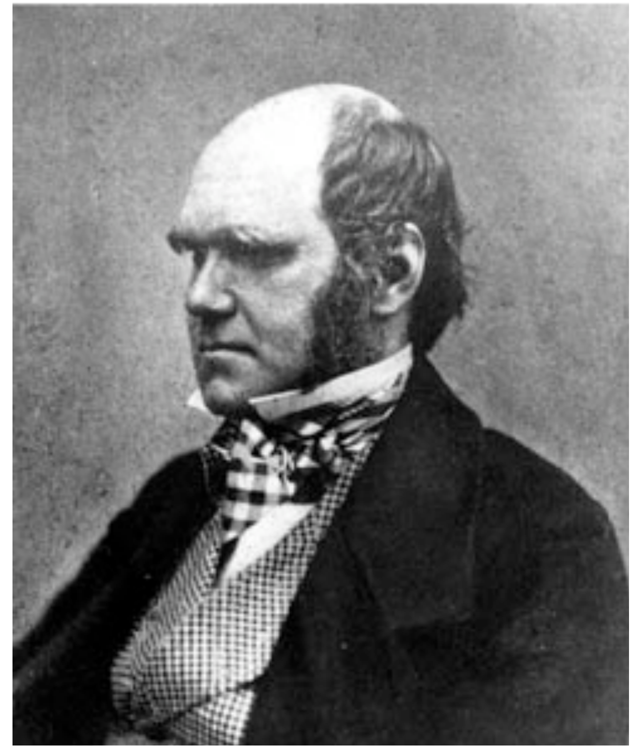
- Field emission is electrons (electrions),
- Electron emission may imply ion emission (damage),
- Local fields of ~ 9.6 GV/m would do this,
- Tensile strength is an important parameter,
- Better experiments are needed.

We agree with him.



Modeling is necessary.

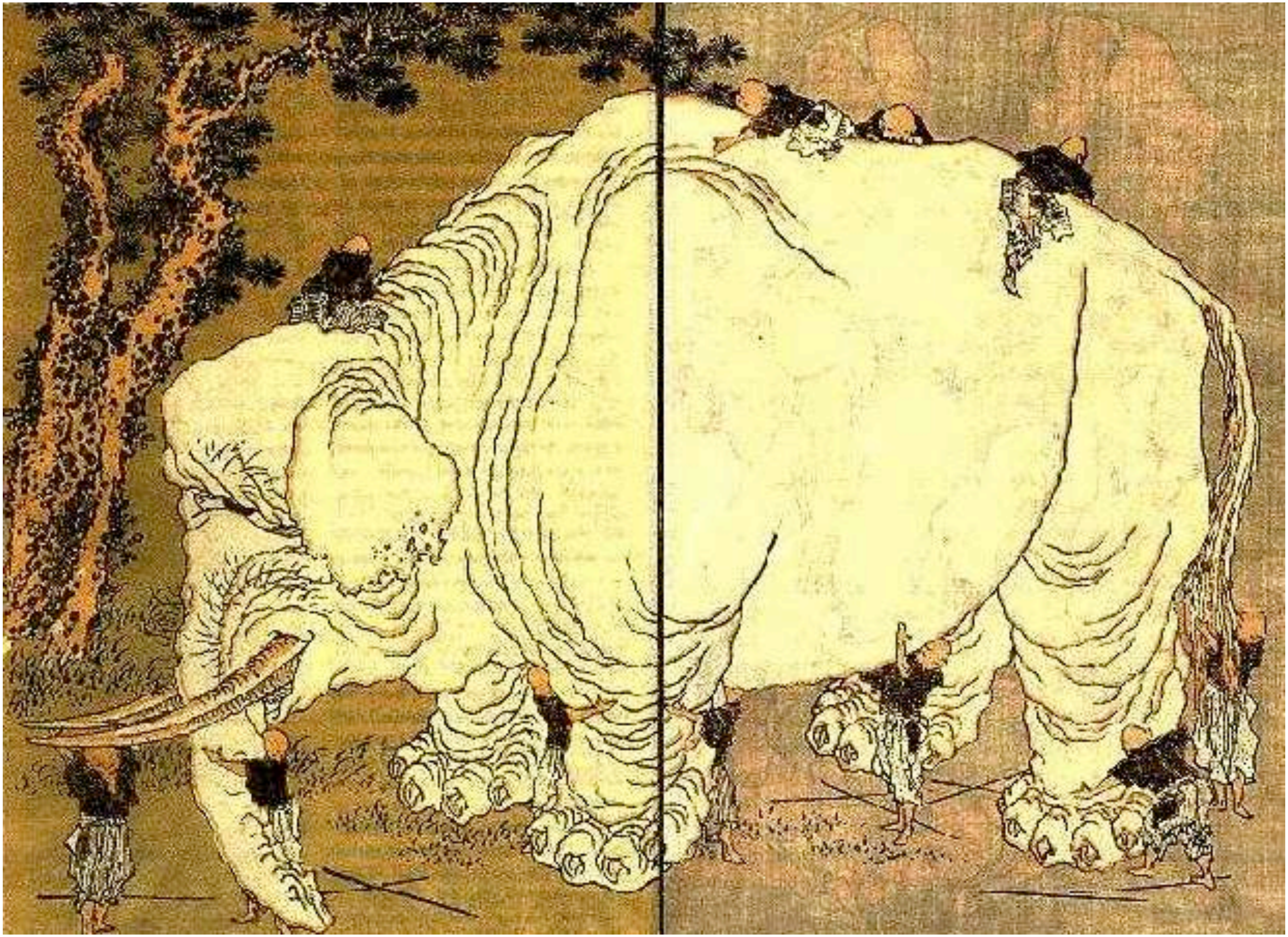
- "About 30 years ago there was much talk that geologists ought only to observe and not theorize; and I well remember someone saying that at this rate a man might as well go into a gravel-pit and count the pebbles and describe the colours. How odd it is that anyone should not see that <u>all observation must be for or against some view if it is to be of any service.</u>"



Charles Darwin, 1861

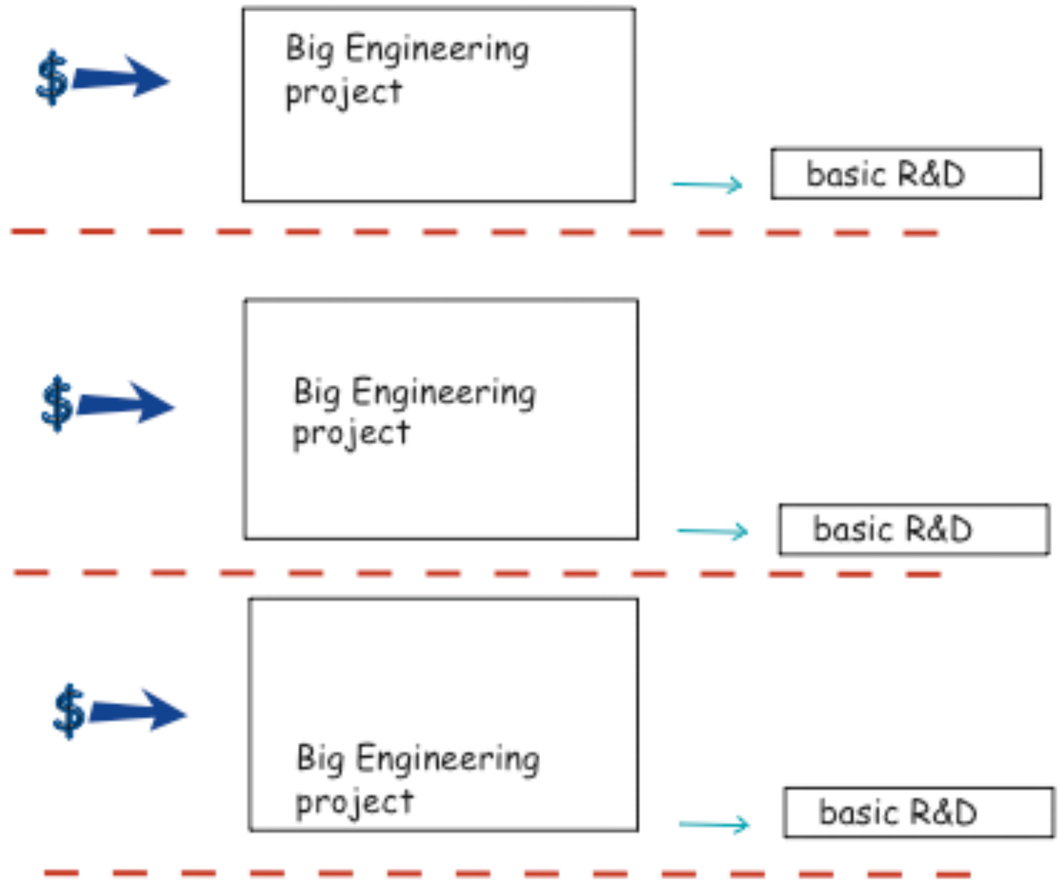
Exp. Problem: Discharges (~10 GW) obscure the trigger signal.

Hokusai 1818



Bureaucratic Problem: Funding is divided up.

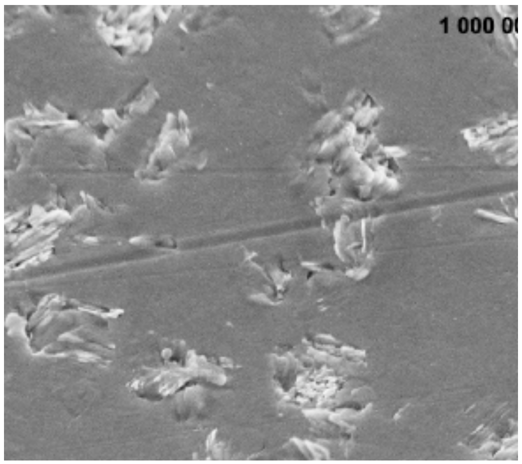
- Individual Projects are funded.
- Each decides R&D priorities separately.
- Common problems suffer.



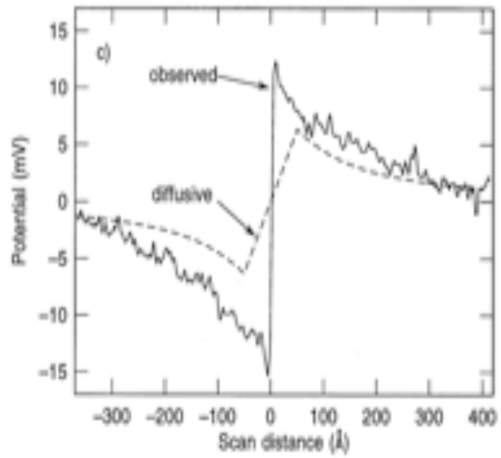
Can ILC and CLIC be limited by the same mechanism?

CLIC and ILC may be limited by the same mechanism, but the two problems cannot be studied together - and aren't studied separately.

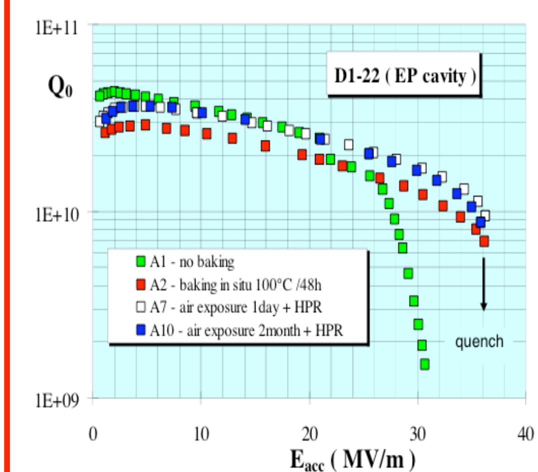
CLIC Fatique studies



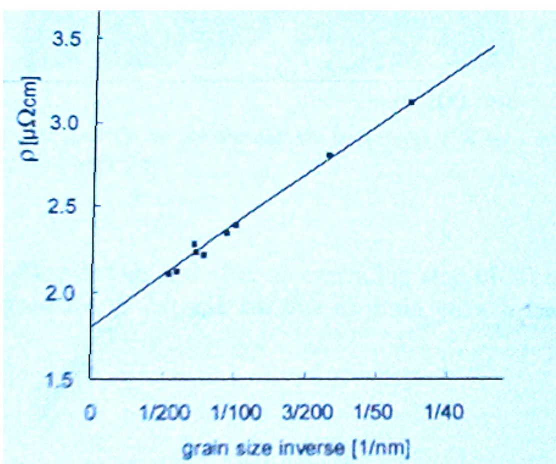
Grain boundary

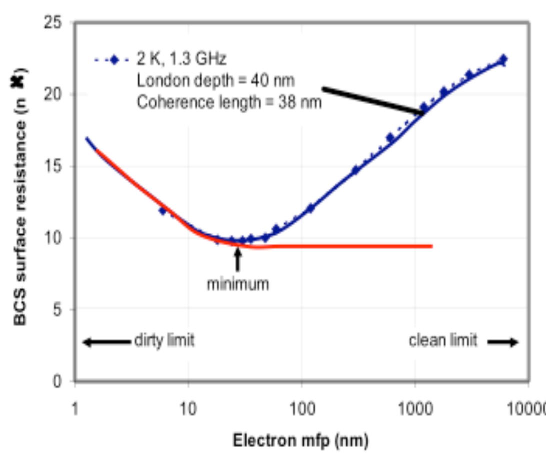


High Field Q-Slope



$\rho \sim n_{GB}$



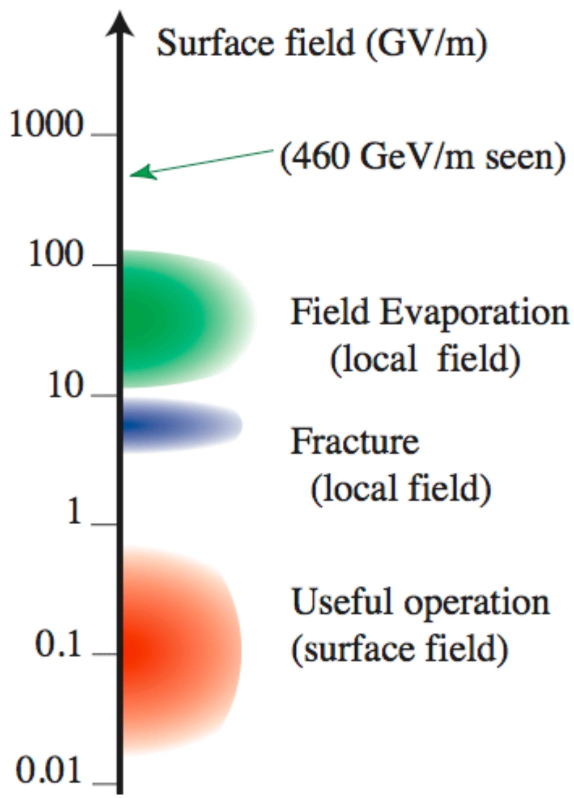


SCRF

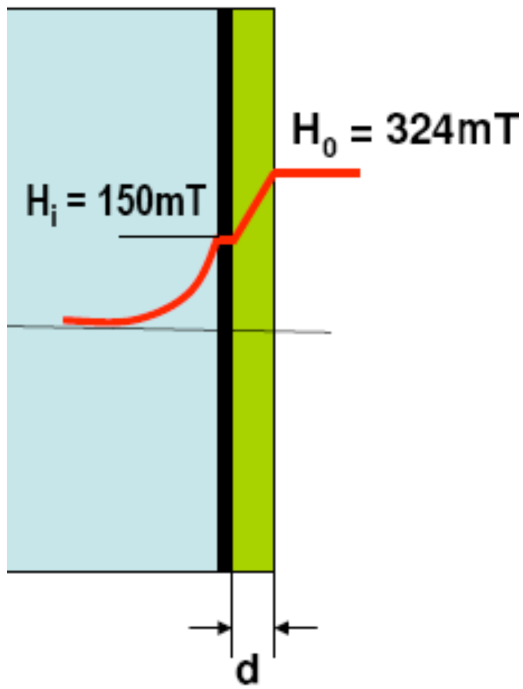
What are the limits of acceleration technology?

- The conventional wisdom, Metals limited to 50 – 70 MV/m, seems wrong.

Normal Metal

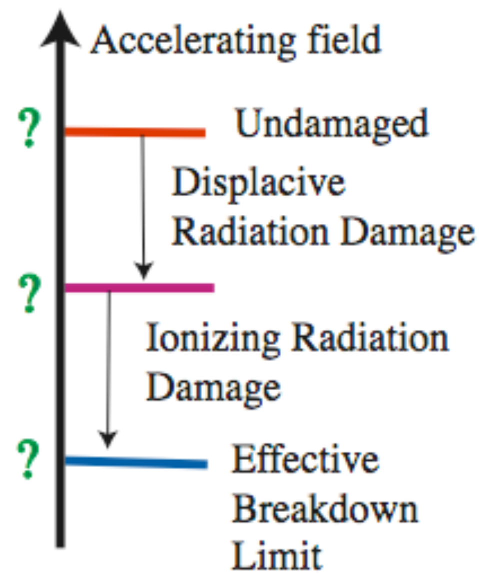


SuperConducting RF



Gurevich layers

Dielectrics



- **Limits are unknown, material science needed.**

Our approach to breakdown, try everything

Part of the Neutrino Factory and Muon Collider Collaboration - Muon Cooling

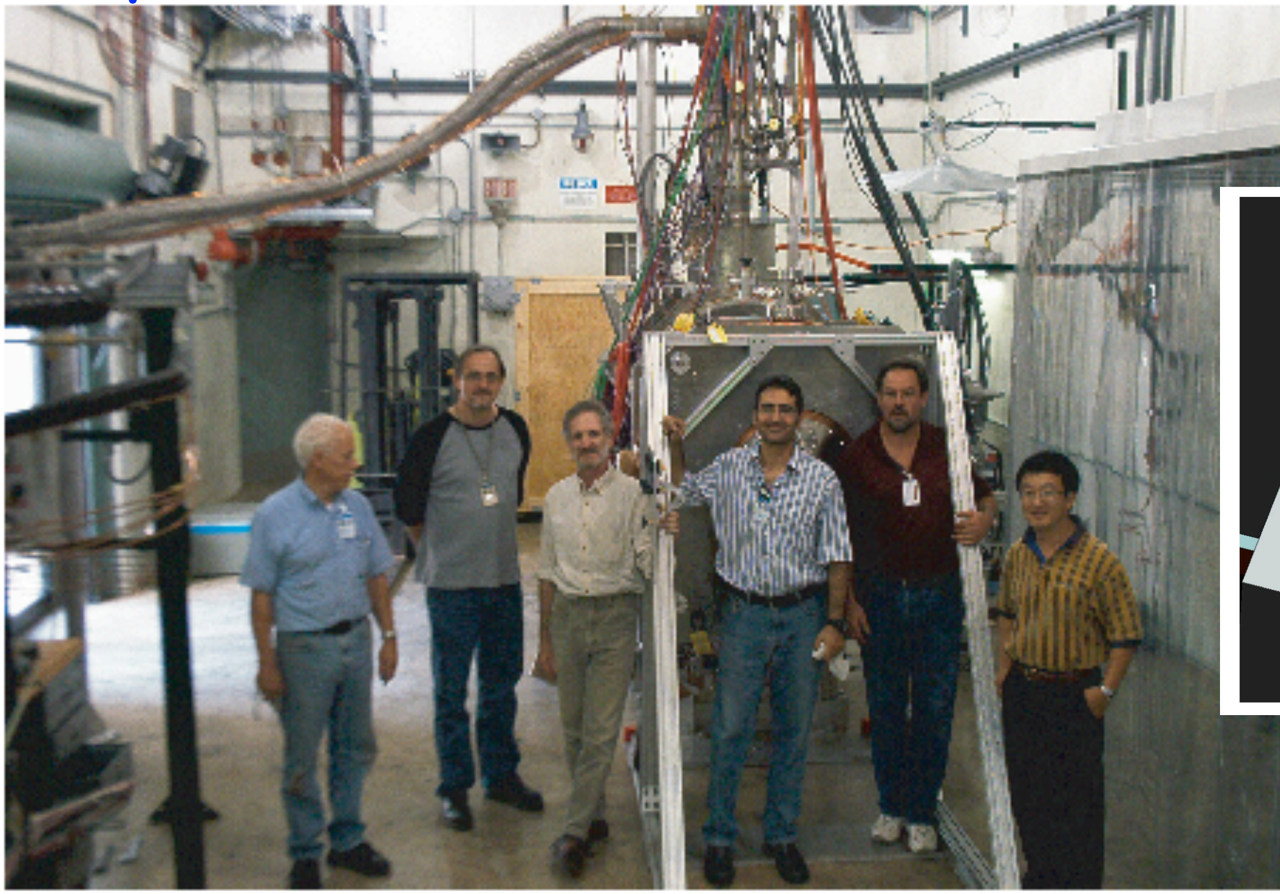
- Experiments in Fermilab MuCool Test Area (MTA) , aimed at MICE
  - J. Norem, Argonne
  - A. Moretti, A. Bross, Z. Qian, B. Norris, FNAL
  - Y. Torun, IIT
  - D. Li, M. Zisman, S Virostek LBNL
  - R. Rimmer, JLab
  - R. Johnson, P. Hanlet, et. al, Muons Inc.
  - + many others

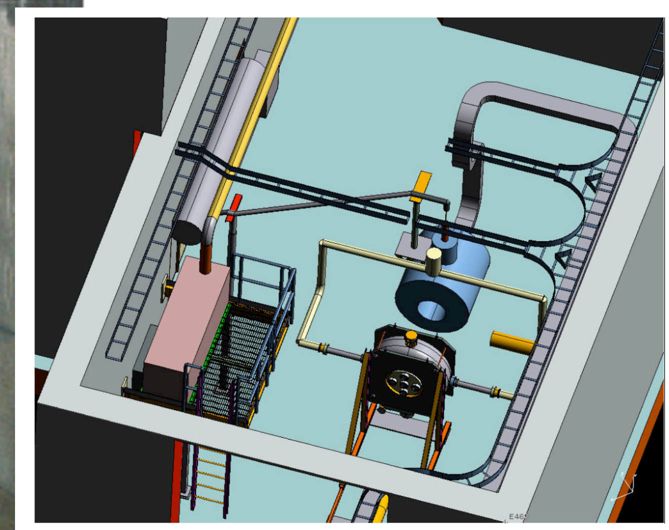
- Modeling of breakdown and cavity parameters
  - Z. Insepov, A. Hassanein, ANL

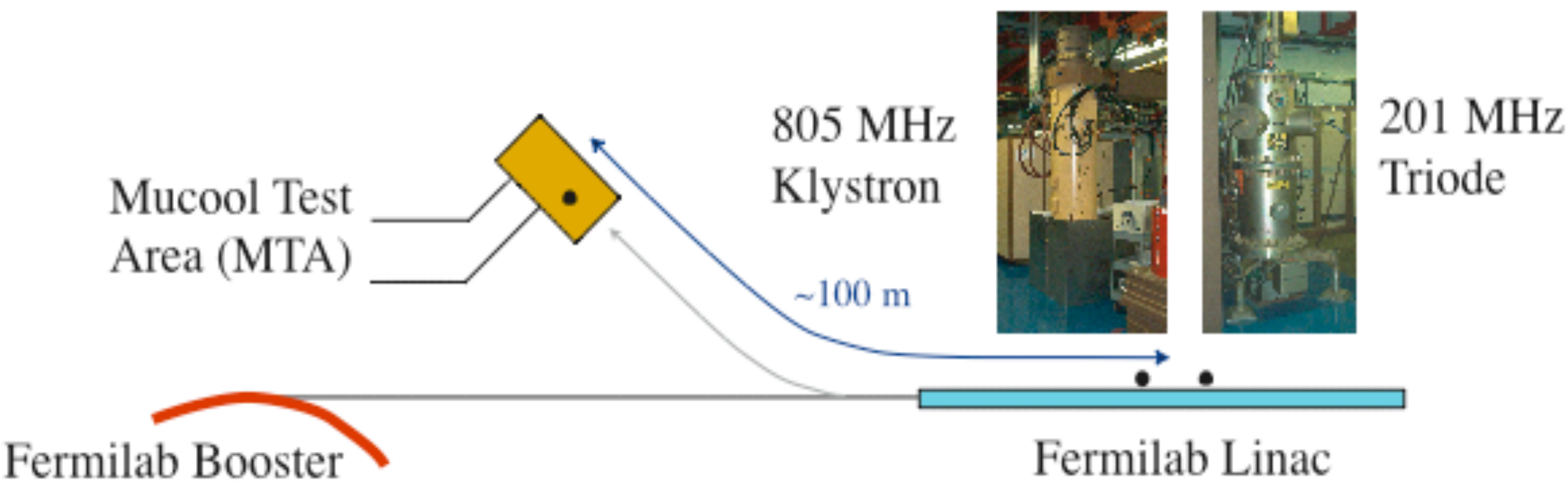
- Surface studies with Atom Probe Tomography at Northwestern Univ.
  - D. Seidman, K. Yoon, NW

- 9th year of experimental program, 6th year with data.
- 59 pages published in referred journals.

RF experiments are in the MuCool Test Area (MTA) at Fermilab



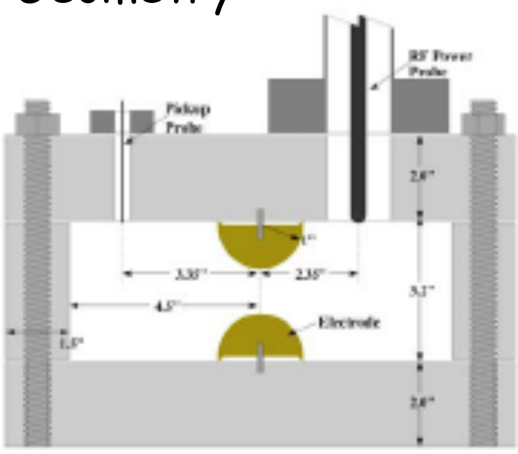




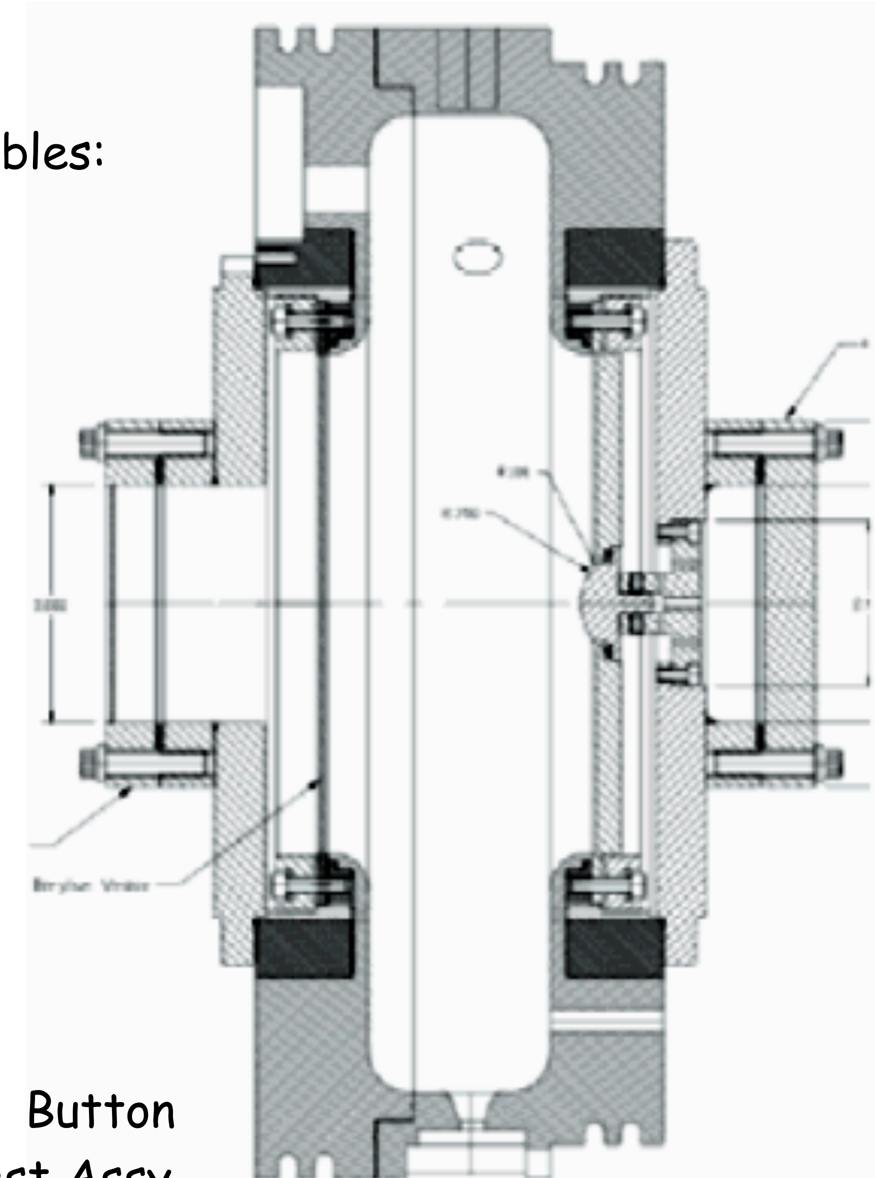
Our 805 MHz program.

We have unique hardware, can study many variables:

- Operation: 201 vs. 805 MHz.
- Magnetic field: 0 – 5 T solenoid on the 805.
- Materials: Cu, Be, SS, Mo, Mo(alloys), W, Nb
- High Pressure (Muons Inc.) H_2 and He
- Window Geometry



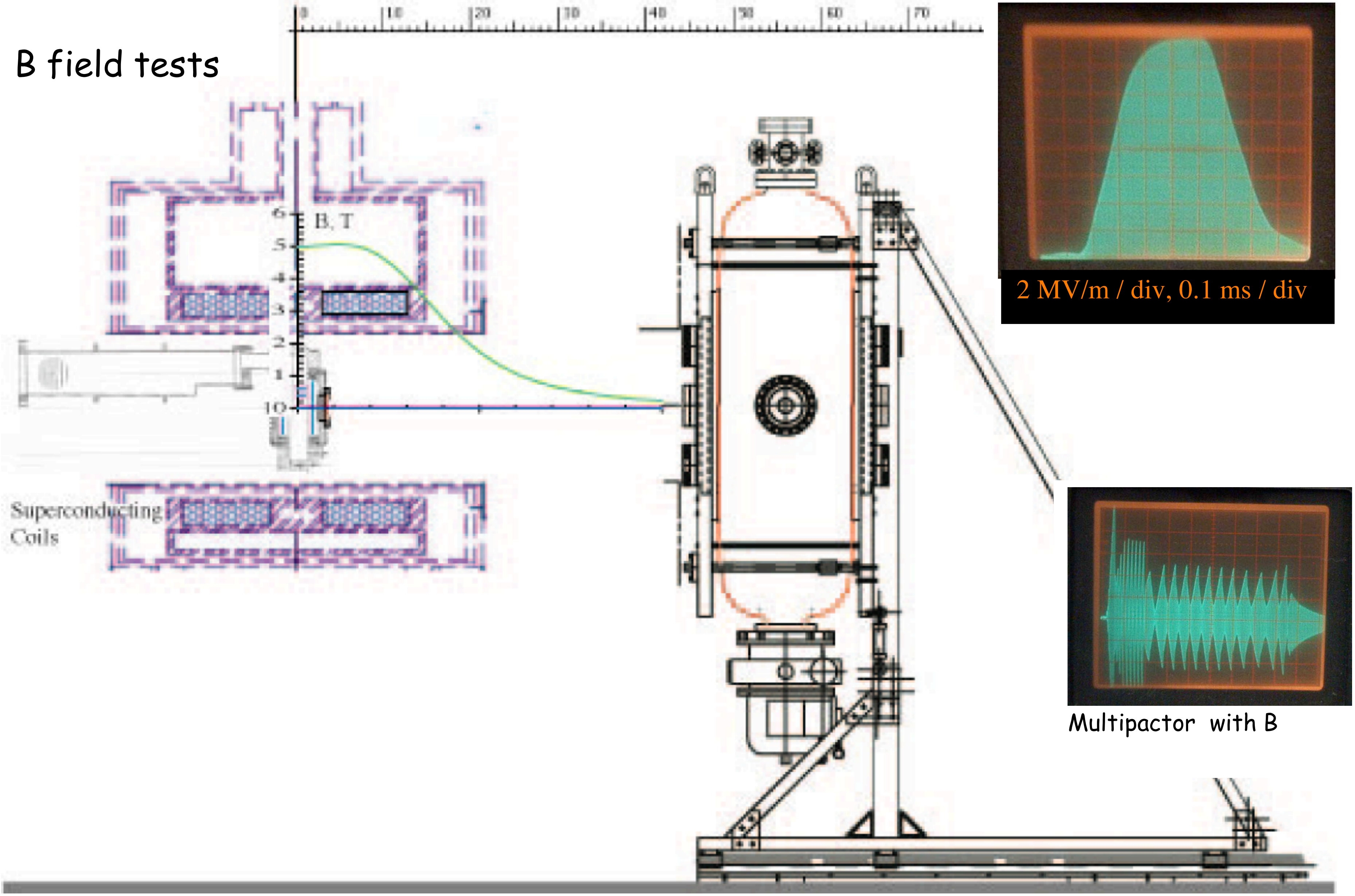
Muons Inc.



Button Test Assy.

201 MHz Program.

- Conditioning / breakdown, window tests.
- B field tests



16 MV/m with B=0

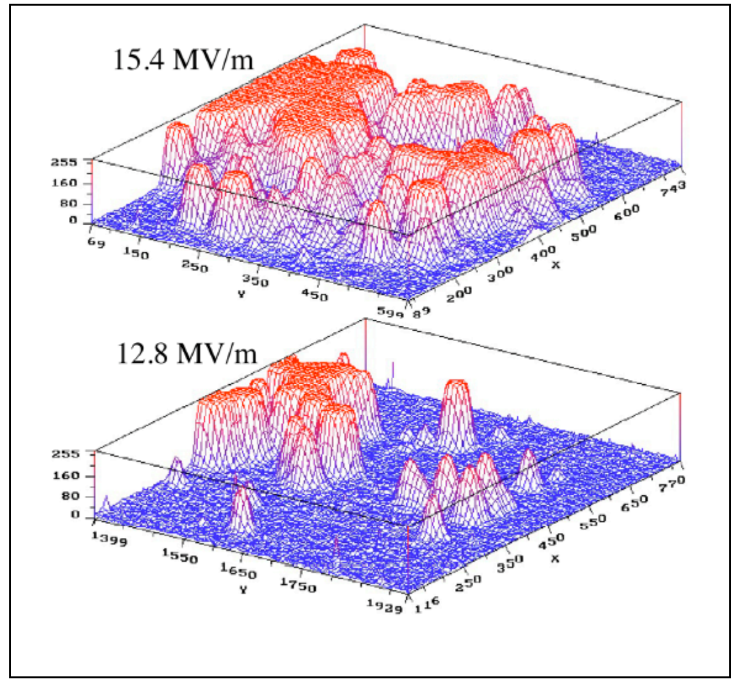
2 MV/m / div, 0.1 ms / div

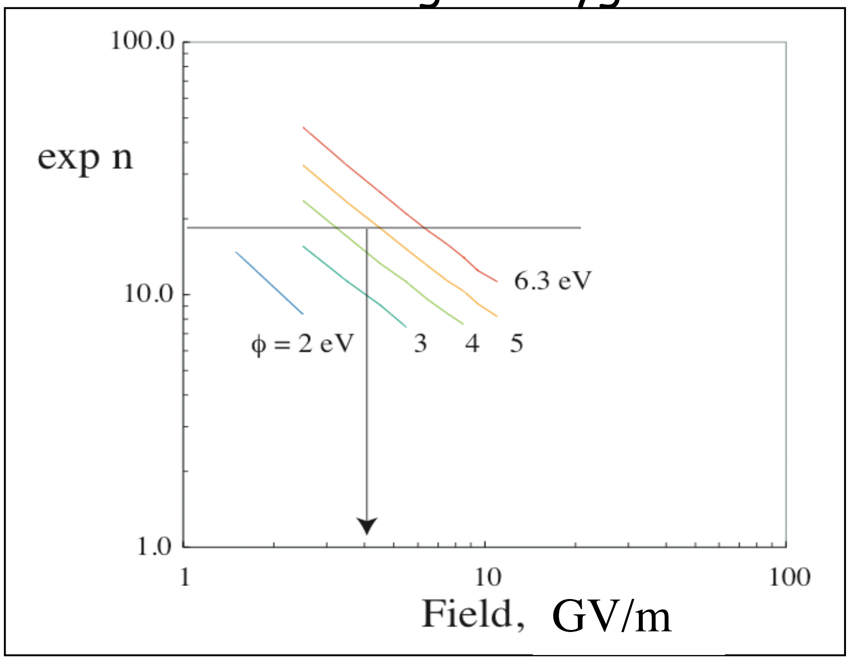
Multipactor with B

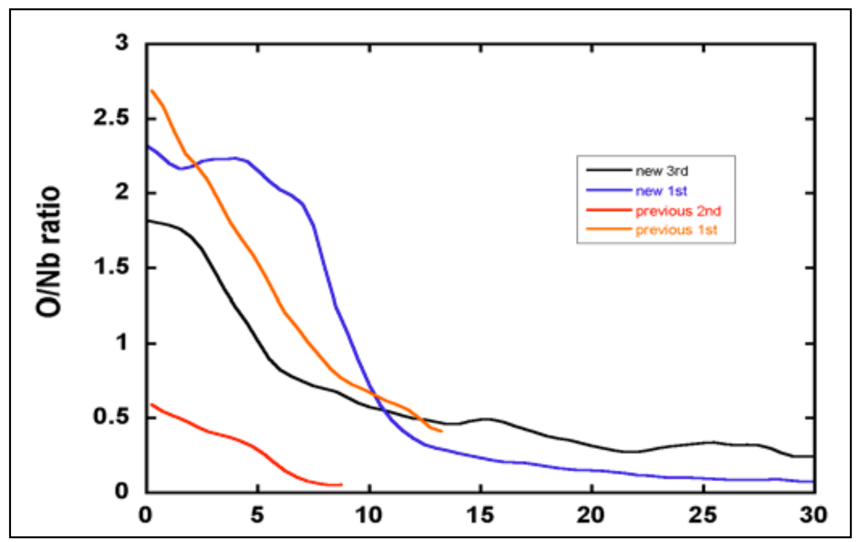
Innovations

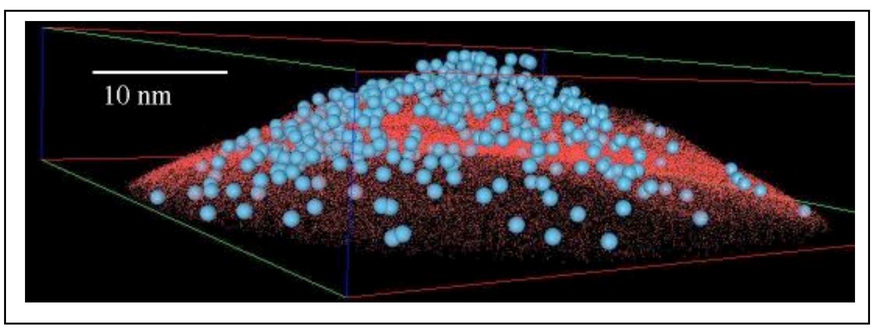
- Simplified Fowler-Nordheim model
- Measurement of properties of emitters on operating cavities
- Use of Atom Probe to study high fields

  Useful for looking at oxygen in niobium



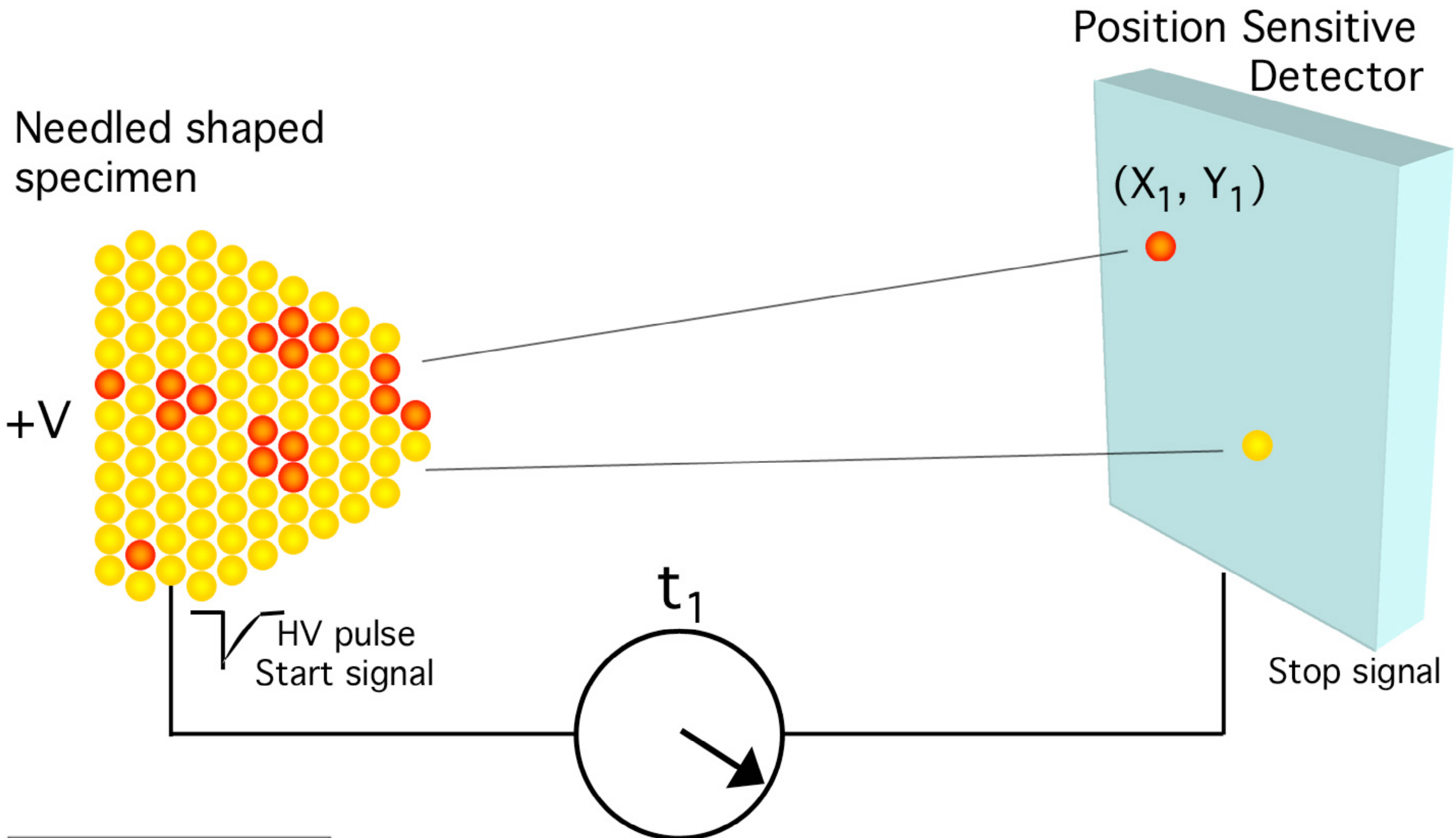






Atom Probe Tomography (at Northwestern)

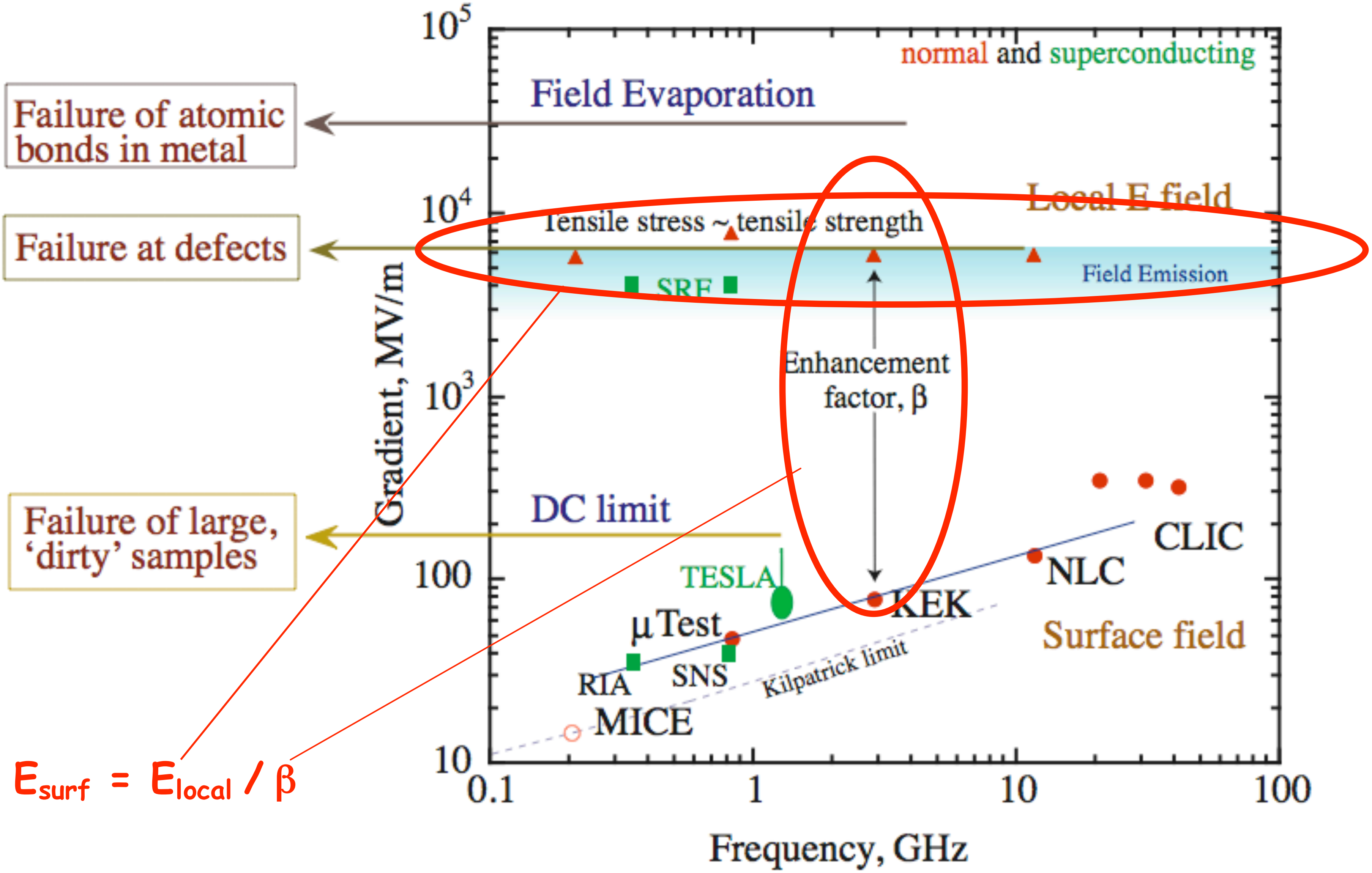
- A systematic way of studying the effects of high fields on material.



NUCAPT
Northwestern University
Center for Atom-Probe
Tomography

<u>500 GeV/m</u> accelerations !

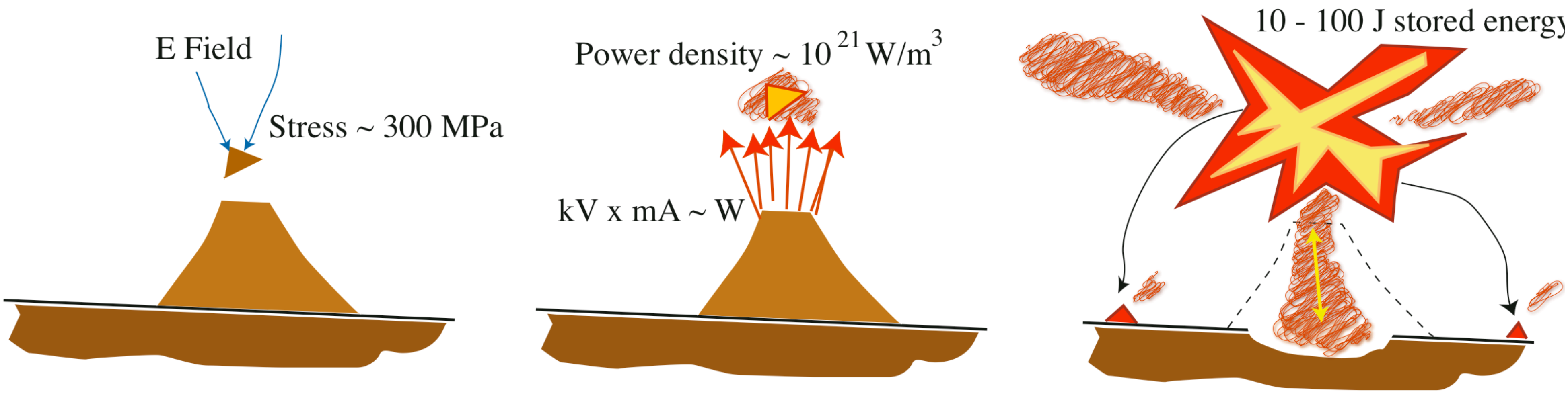
Our Model: Local fields + enhancements determine everything.



$E_{surf} = E_{local} / \beta$

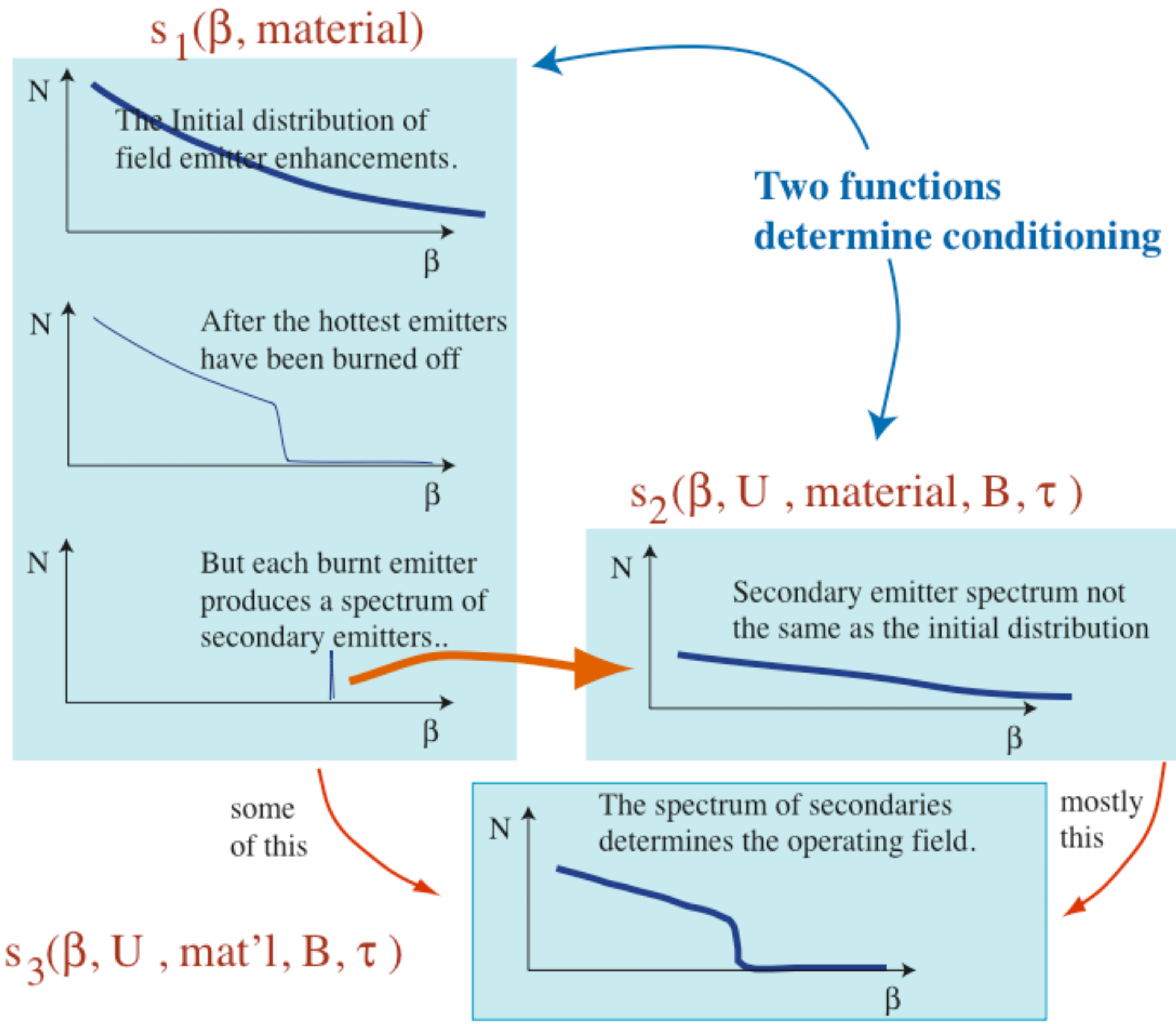
The Process of Breakdown

- Field emission is the diagnostic.
- Fracture is the trigger.
- Field emission heating makes a lossy plasma.
- The lossy plasma directs the EM energy to the wall.
- An equilibrium state develops between the structure and the surface.
- Damage Functions: $s_1(\beta)$, $s_2(\beta)$, $s_3(\beta)$ describe the surface development.
- This is described in refereed papers and conference papers.



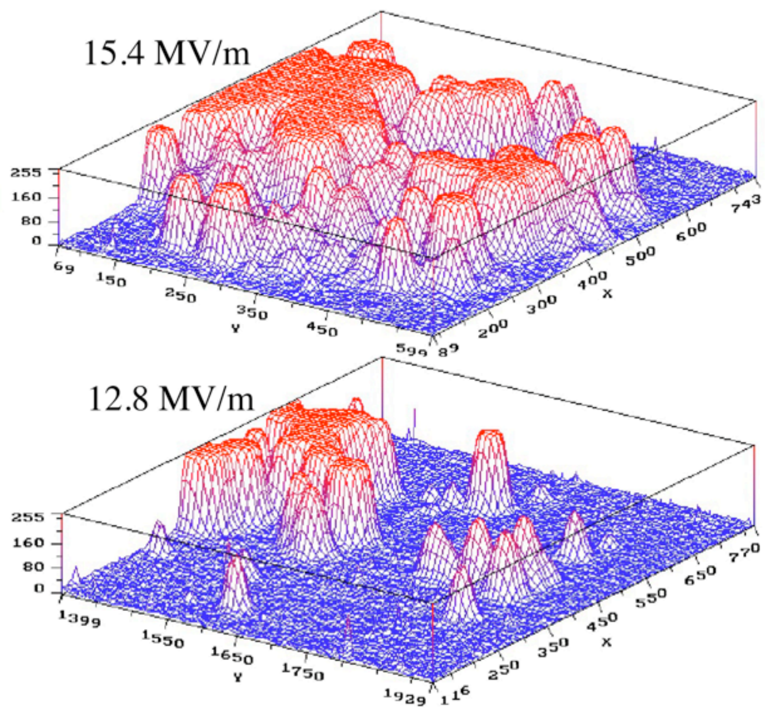
Fracture | Field emission heating | Discharge

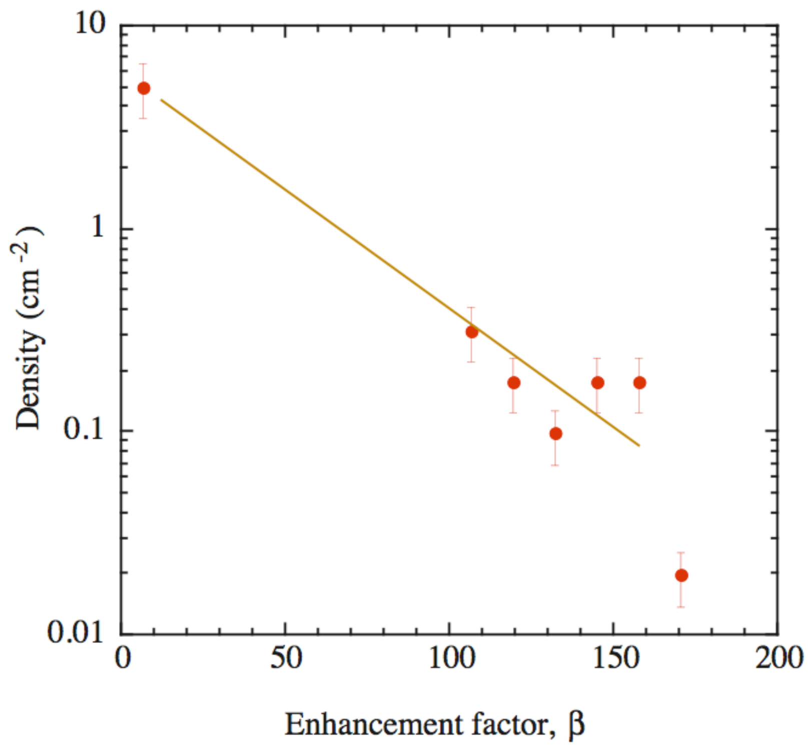
Damage spectra



We have measured $s_2(\beta)$ during cavity operation.

- We looked at individual emitters, and measured spectra produced in discharges



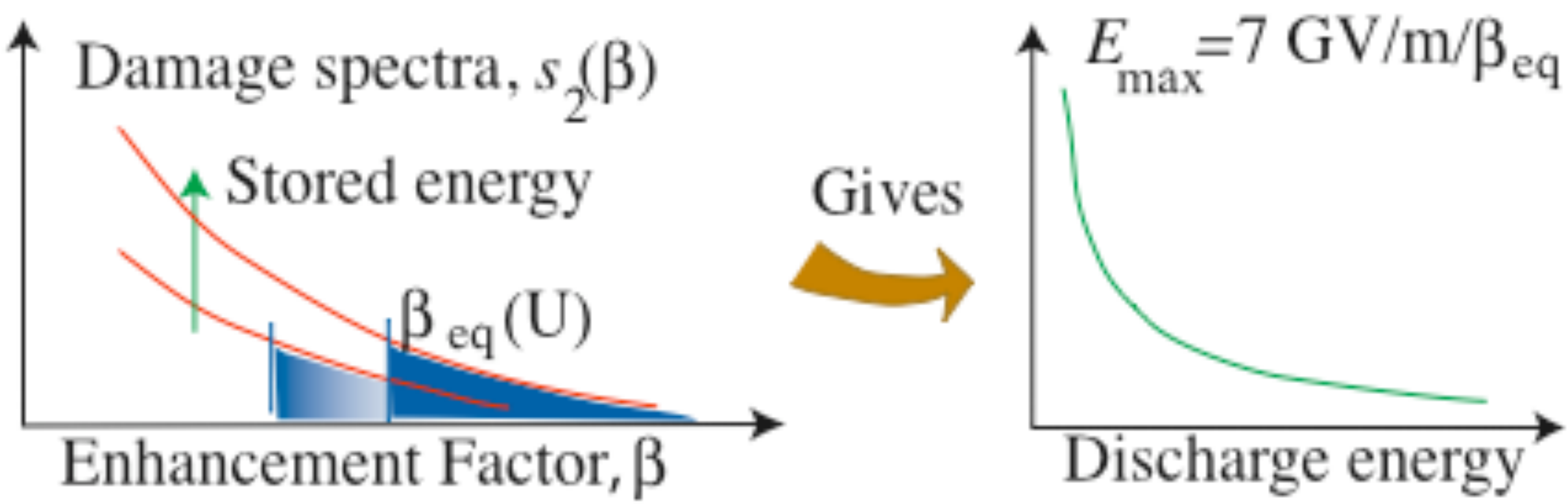


- From the emitter intensities at different fields we can measure the spectrum of field enhancements

The maximum operating field

- Stable operation demands that:
  breakdown events cannot create more damage than they destroy.

- This constraint relates the maximum β and the discharge energy.



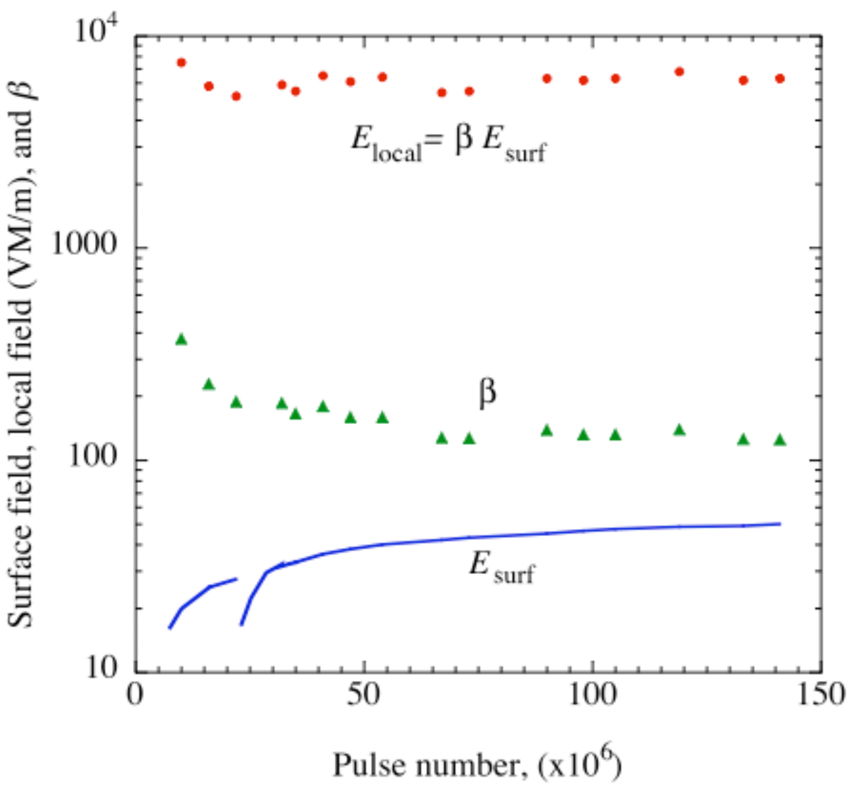
Using the model: I) Conditioning

- Breakdown occurs when E_{local} ~ 7 GV/m

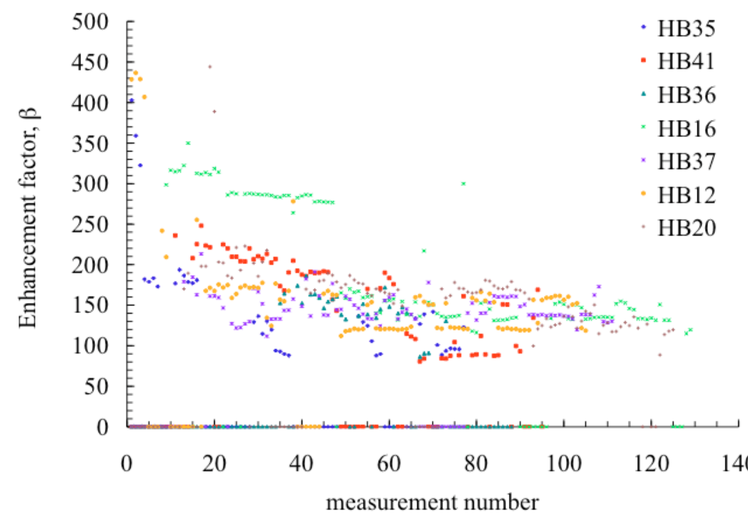
- Only the emitters change, everything else constant.

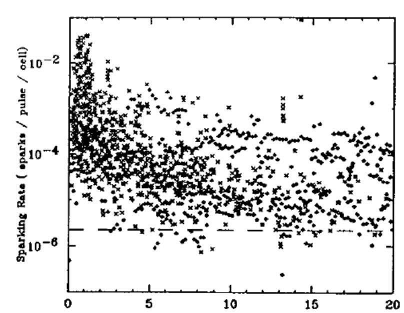
- Superconducting cavities also condition. SNS vs. Fermilab linac

KEK



SNS





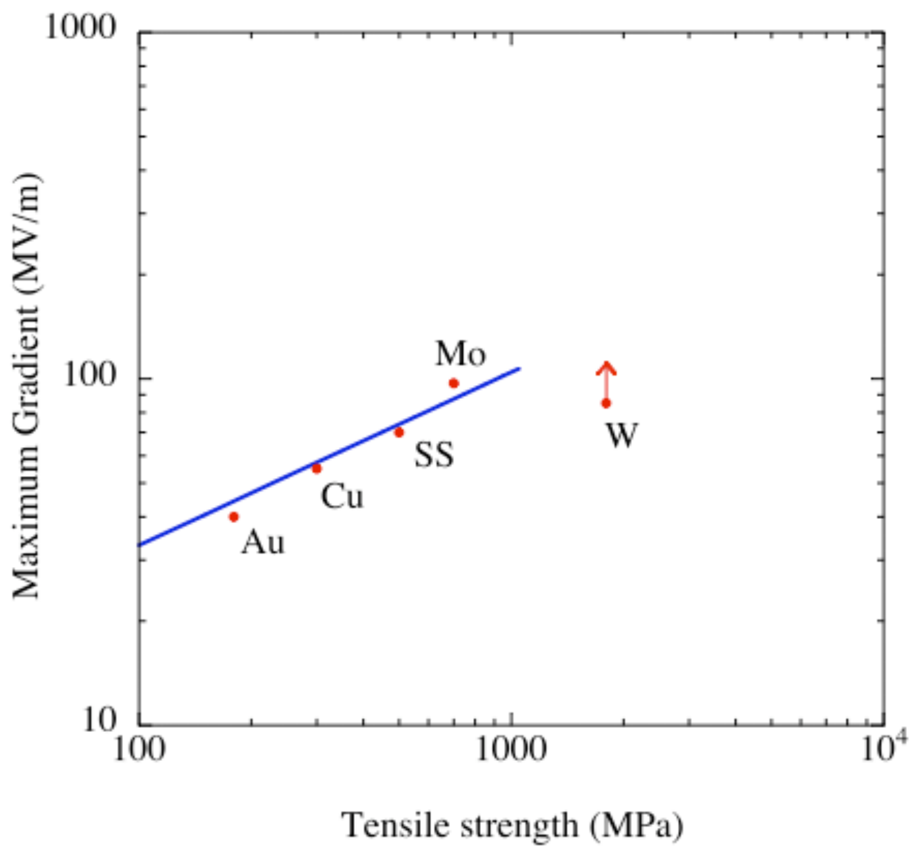
FNAL/linac

Using the model: II) Materials

- Only materials change, everything else constant.

- The model argues that tensile strength is the dominant effect.

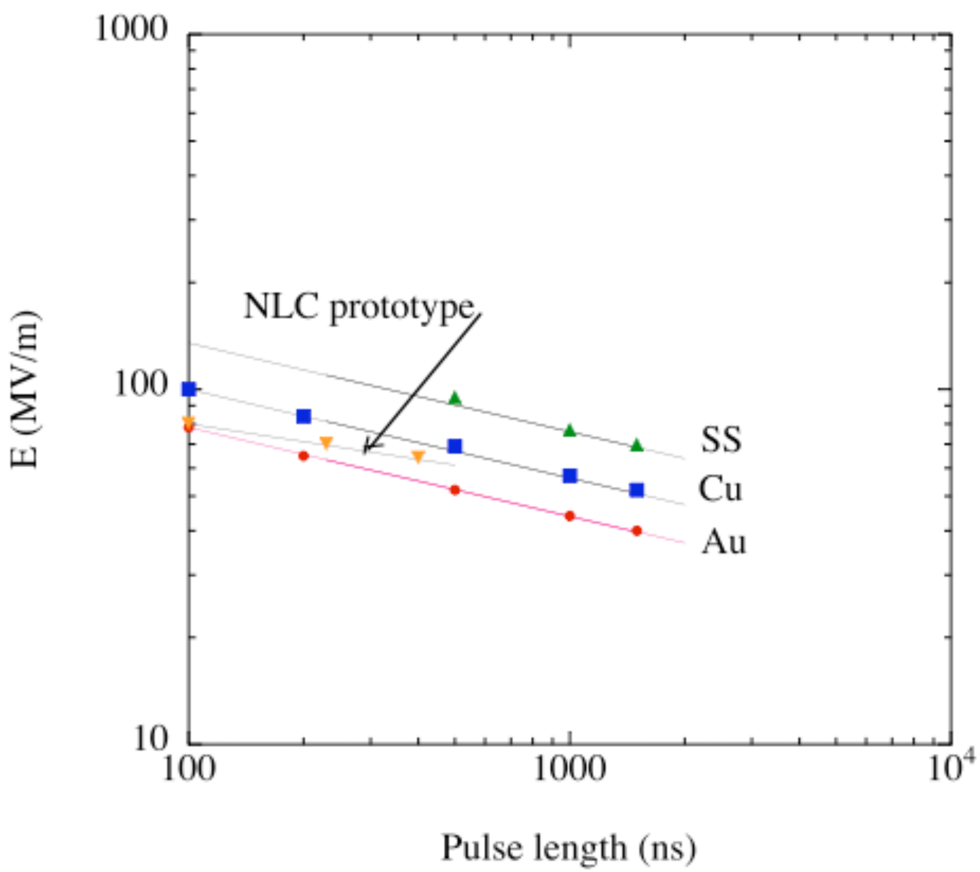
- $$E_{surf} = \frac{E_{local}}{\beta} \approx -\frac{\sqrt{2T/\varepsilon_0}}{\ln(b/a)/b}$$



SLAC and CERN data

Using the model: III) Pulse length

- Only pulse length changes, everything else constant.
- More damage ➜ lower gradients
- Predictions and data show no dependence on position of breakdown within pulse.



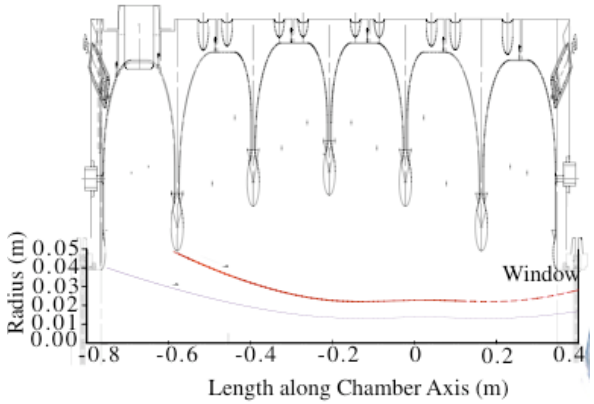
SLAC data

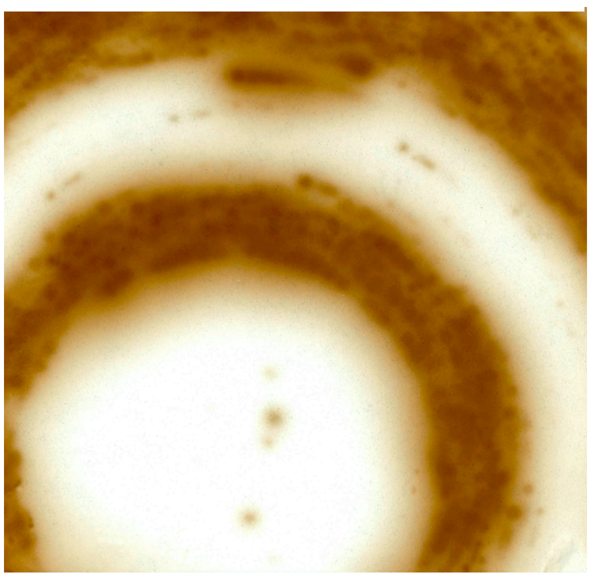
Using the model: IV) The fully-conditioned state

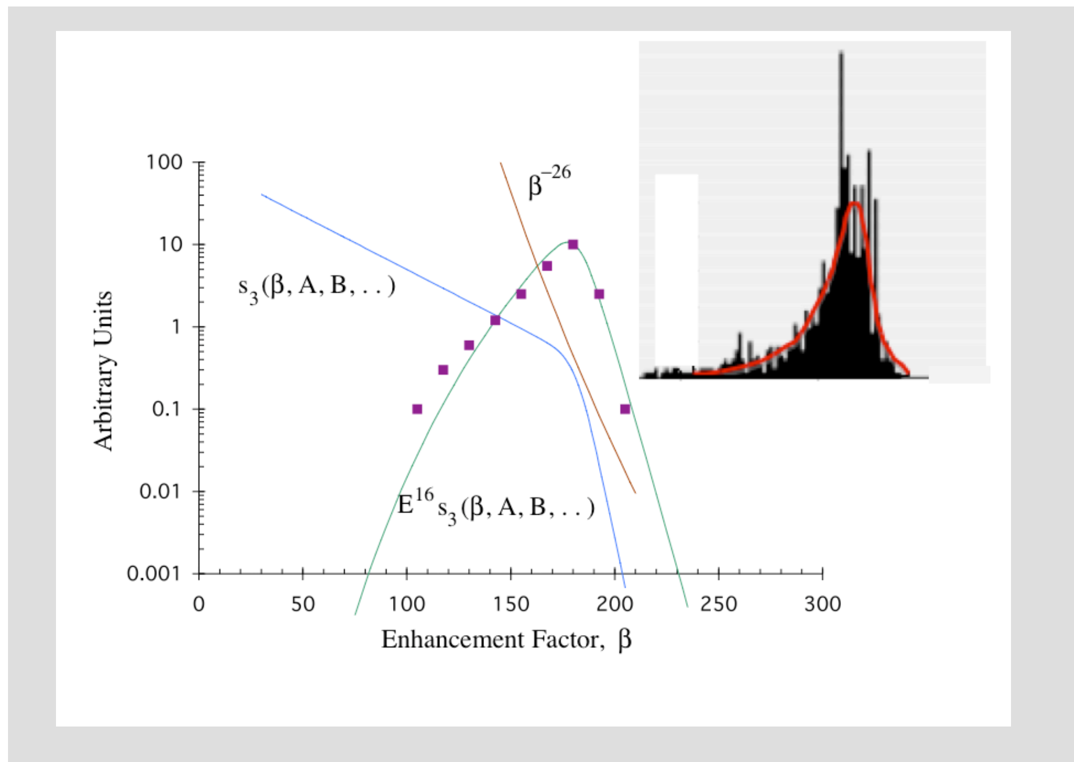
- When you look at emitters, they are all the same strength.
- Assume $s_3(\beta) = s_2(\beta)/(e^{(\beta-\beta_{eq})/c}+1)$ (F-D cutoff - very sharp β^{-25})
- Images of emitters . .. . show emitter strengths

  optical densitometer shows cutoff

  (weighted by field emission I=E^n)

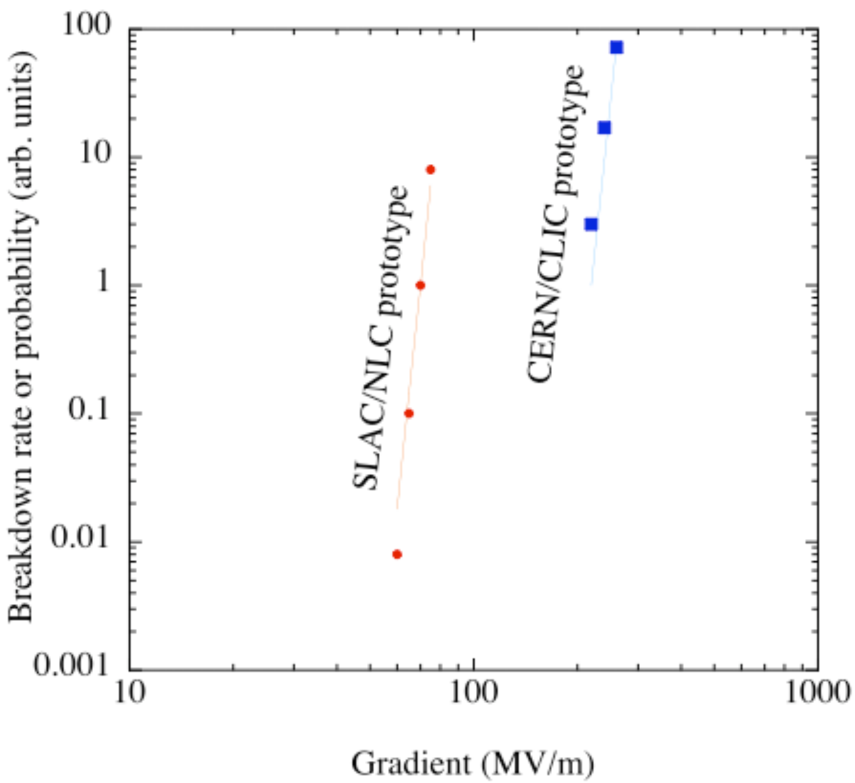






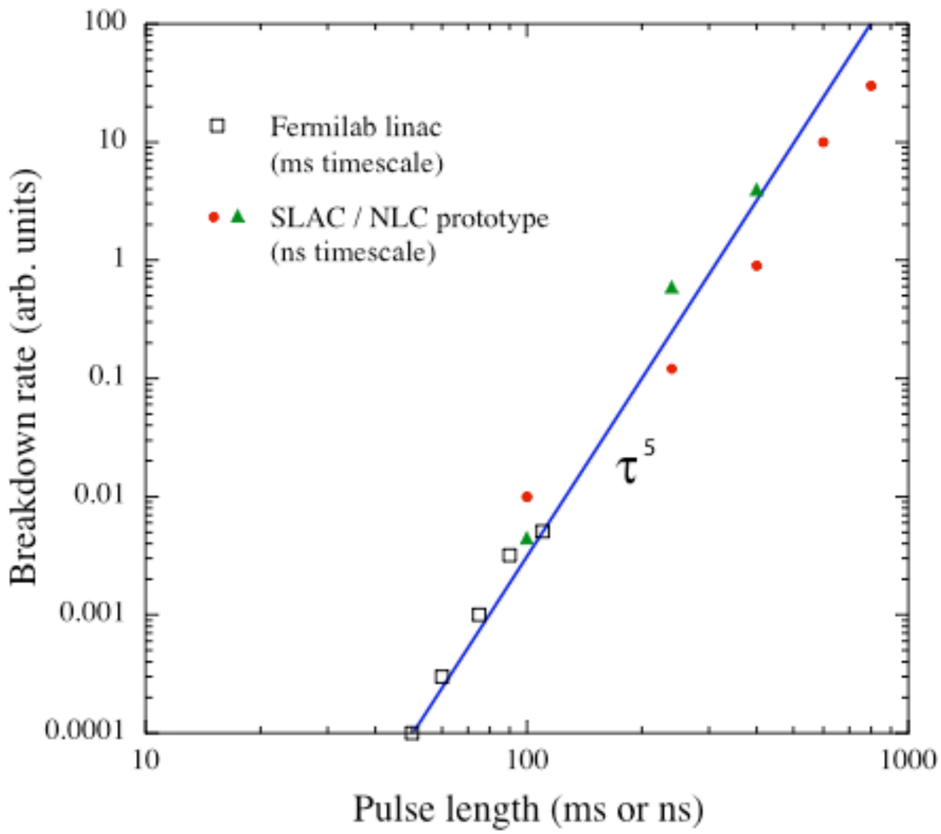
Using the model: V) Breakdown rates vs. *E*.

- These are surprisingly sharp, yet consistent with fully-conditioned state
- Thresholds go like ~E^{25}.



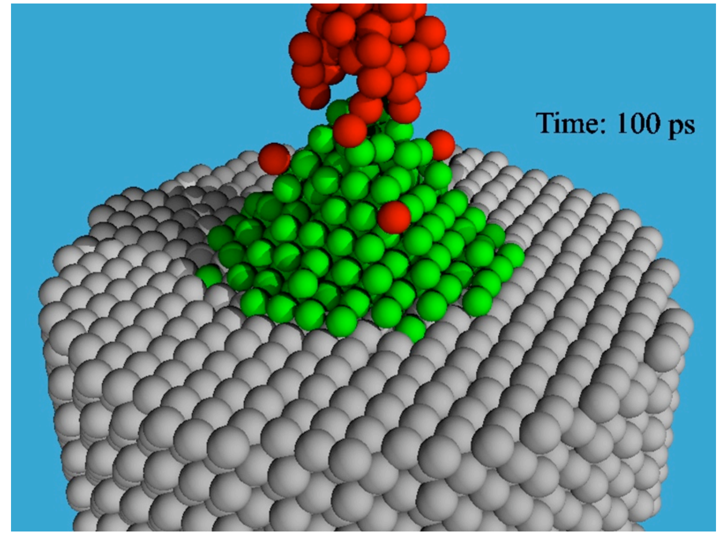
Using the model: VI) Breakdown rates vs. pulse length

- Rate vs pulselength is a function of Rate(E) and $E_{max}(\tau)$, $\left(\dfrac{dR}{d\tau} \sim \dfrac{dR}{dE}\dfrac{dE}{d\tau}\right)$.
- Data from the Fermilab Linac and SLAC/NLC prototype follow τ^5, as predicted.



Using the model: VII) Temperature dependence

- A molecular dynamics model predicts little temperature dependence. (Insepov)
- This is consistent with CERN/CLIC results.



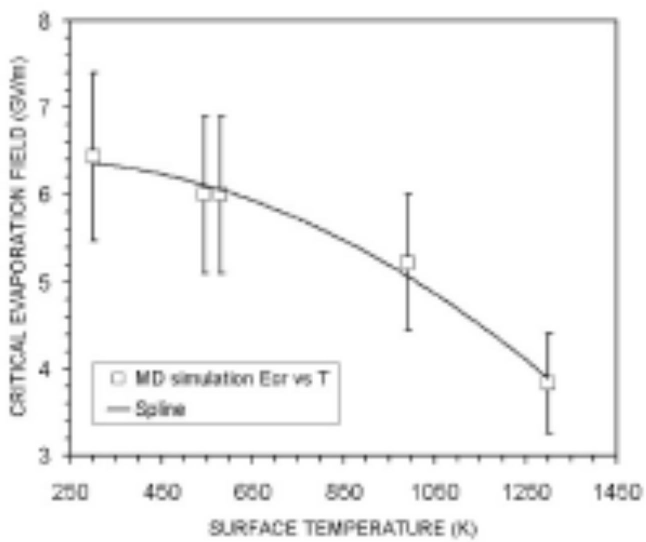


FIG. 2. Observed temperature dependence of critical evaporation field for removing cluster of ~ 200 Cu ions.

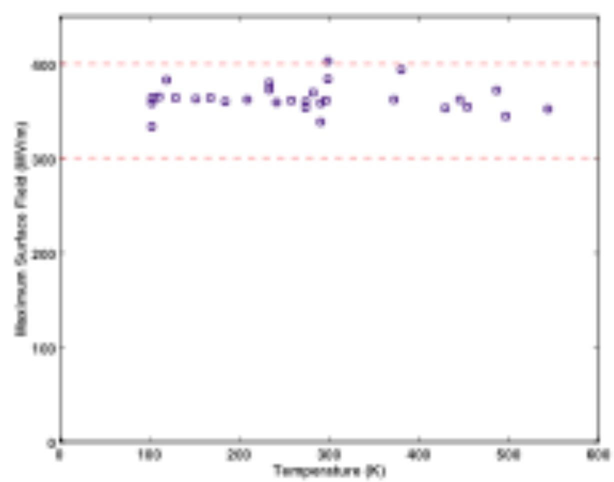


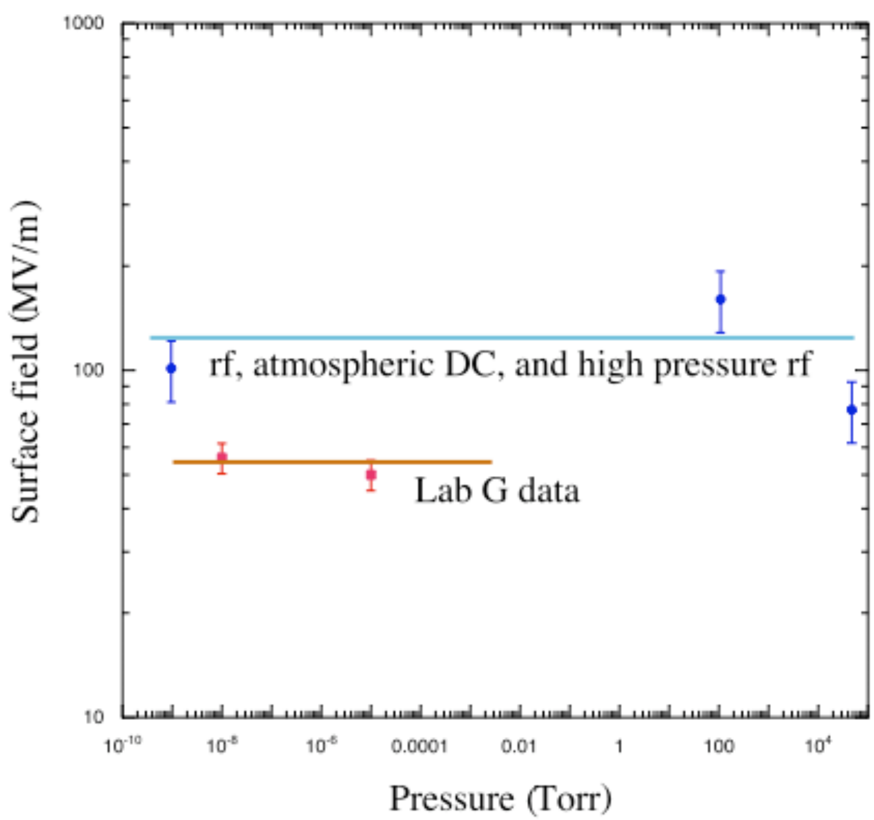
FIG. 6 (color online). Temperature dependence of maximum surface field.

Using the model: VIII) Gas Pressure and type

- Gas pressure retards field emitted electrons heating broken fragments
  This can disrupt the trigger, for low Z gasses.

- Data confirms little effect over >15 orders of magnitude in pressure.

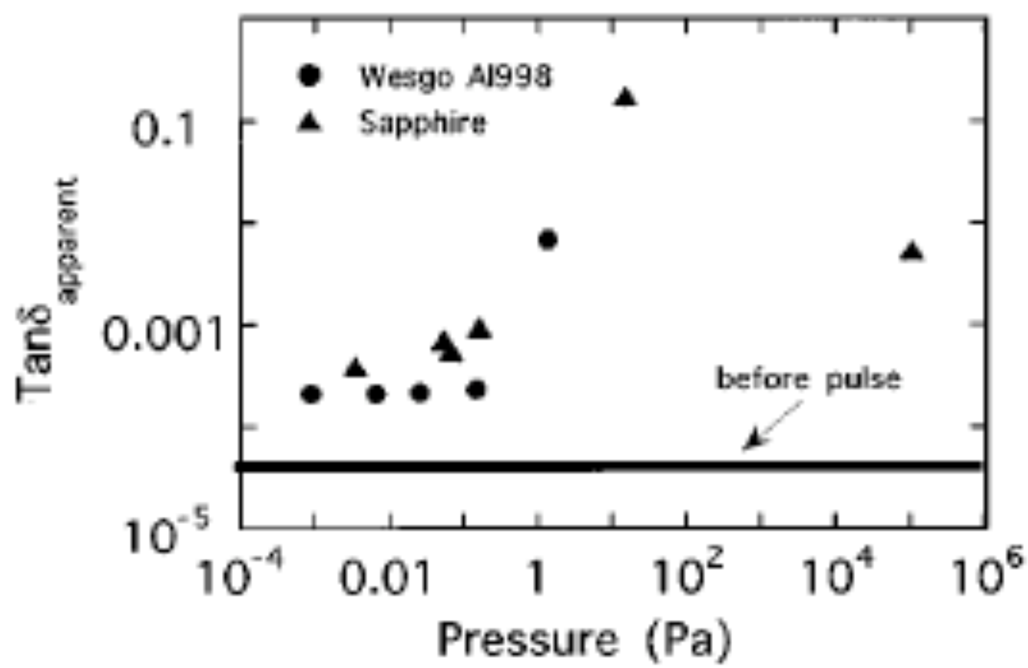
- We can also explain how SF_6 can affect breakdown.



Mucool, Muons Inc and Hist data

Using the model: IX) Dielectrics

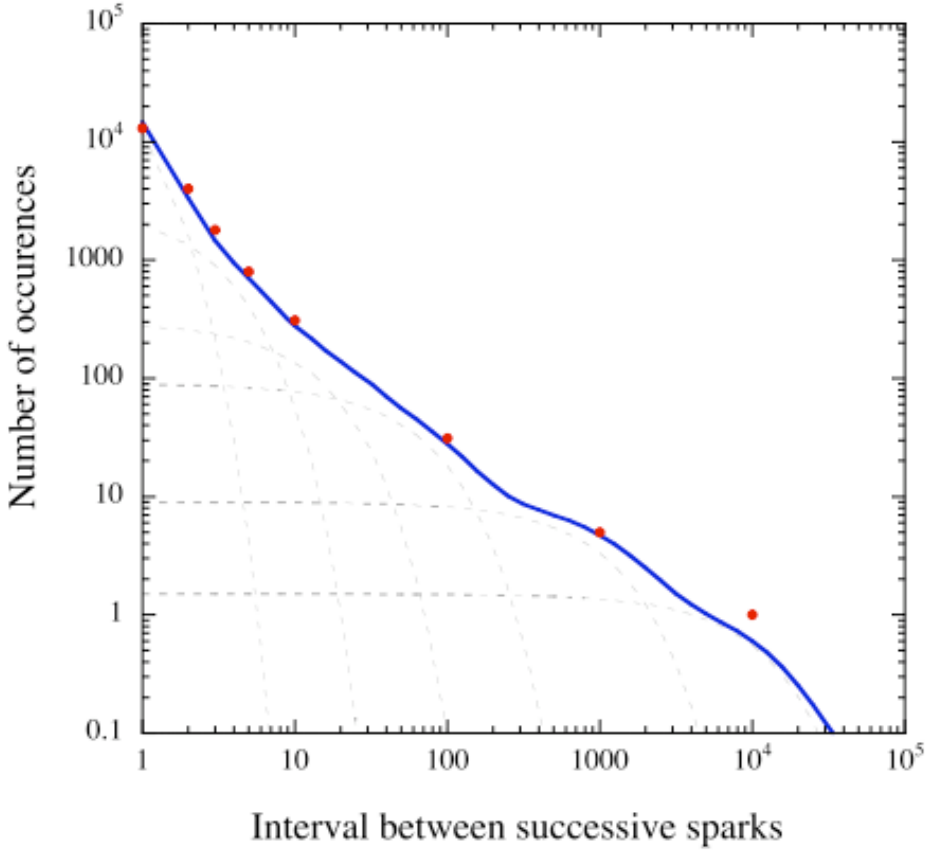
- High pressure gasses are an option for muon cooling.
- Realistic muon beams require Gas + High Gradient + Radiation
- Radiation comes two ways: 1) ionizing, and 2) displacive.   1) is our problem.
- We can measure loss tangents vs. Pressure in a radiation environment.
- Losses are radiation and pressure dependent.



Using the model: X) Spitfests

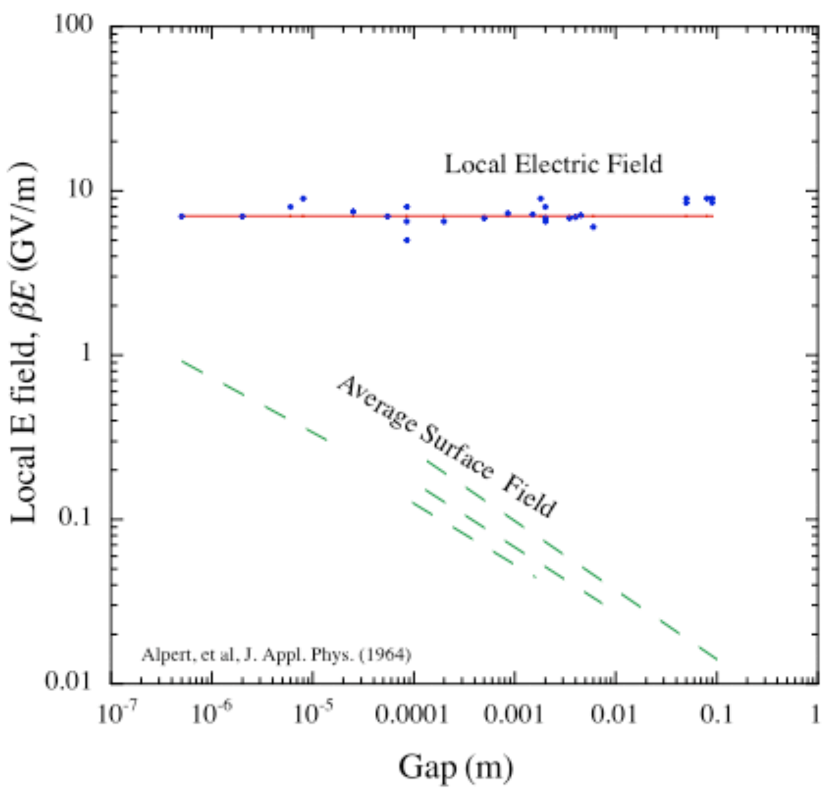
- Correlated breakdown events measure breakdown site lifetime.
- Fatigue theory relates strain to lifetime. A spectrum of strains seems required.

FNAL linac data



Using the model: XI) DC breakdown

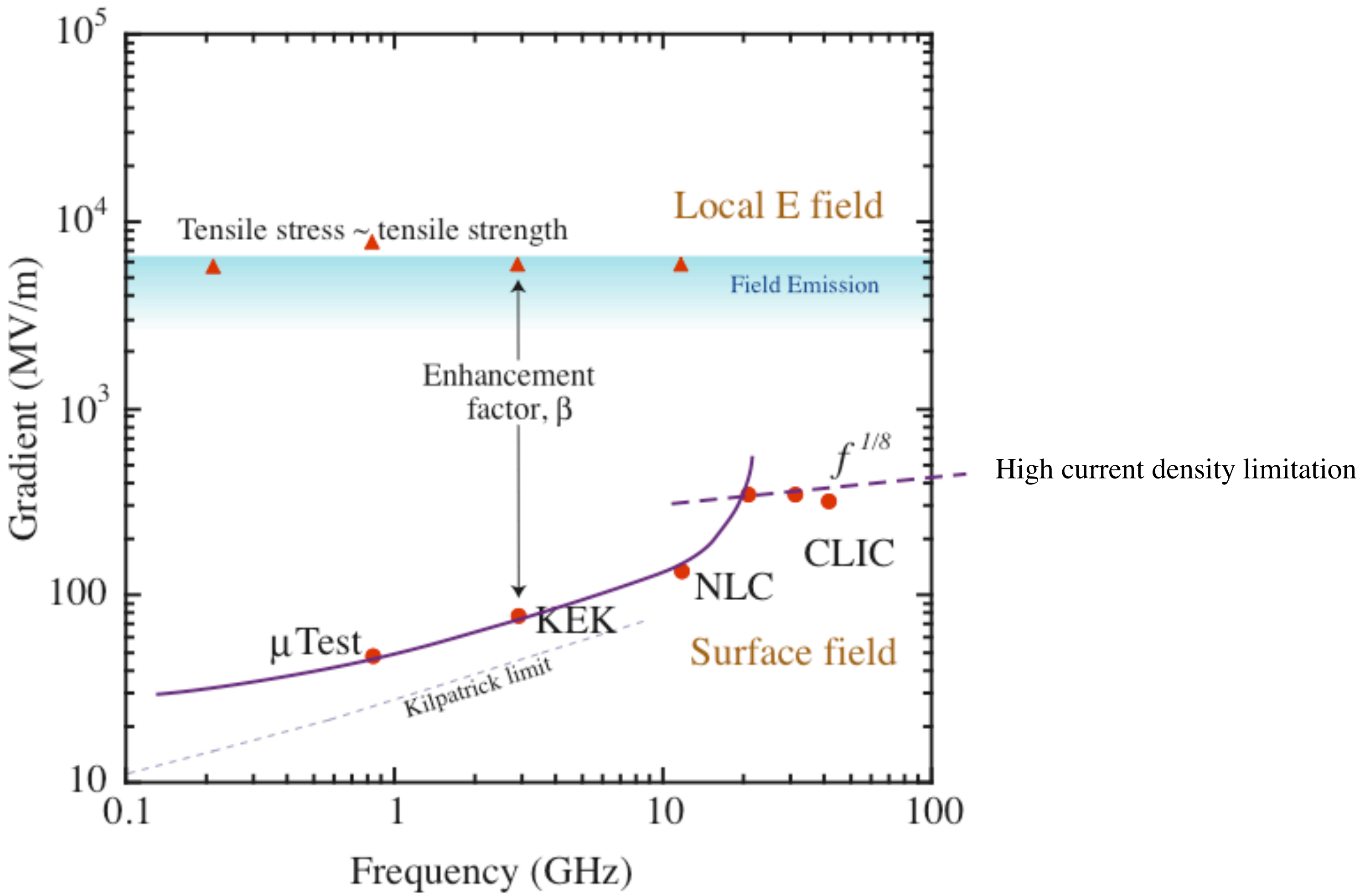
- This also fits the model, with breakdown at 7 GV/m.
- Most of this data is very old and unreliable, but they did clever things.
- Vacuum and cleaning techniques were not always well done.



Alpert et al (1964)

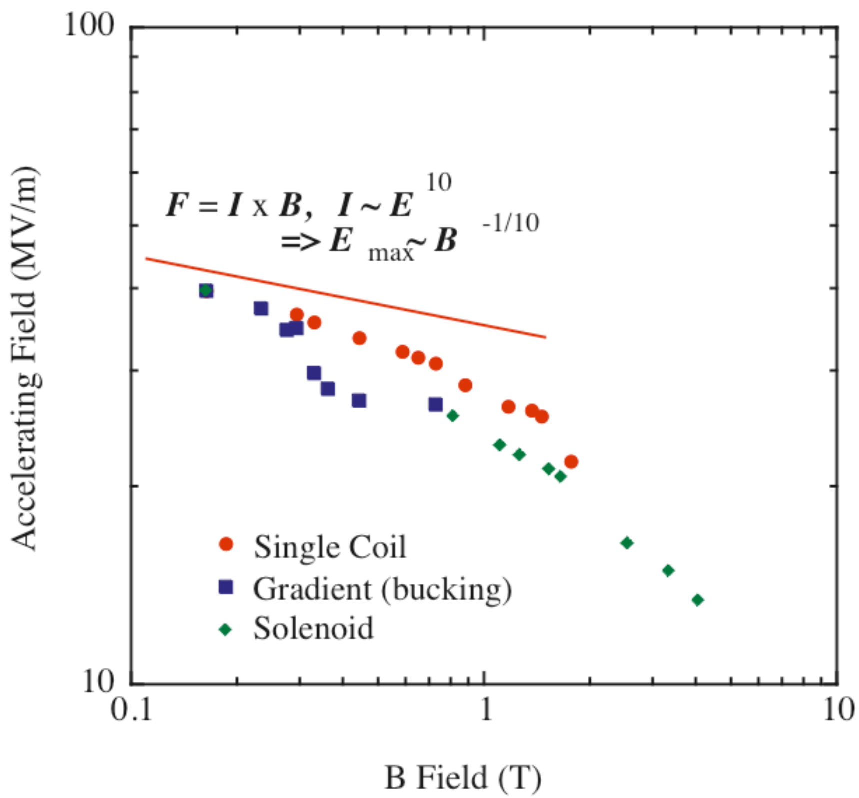
Using the model: XII) Maximum field vs. frequency

- Each cavity / PS system is unique.
- Our model gives Kilpatrick-like scaling laws.



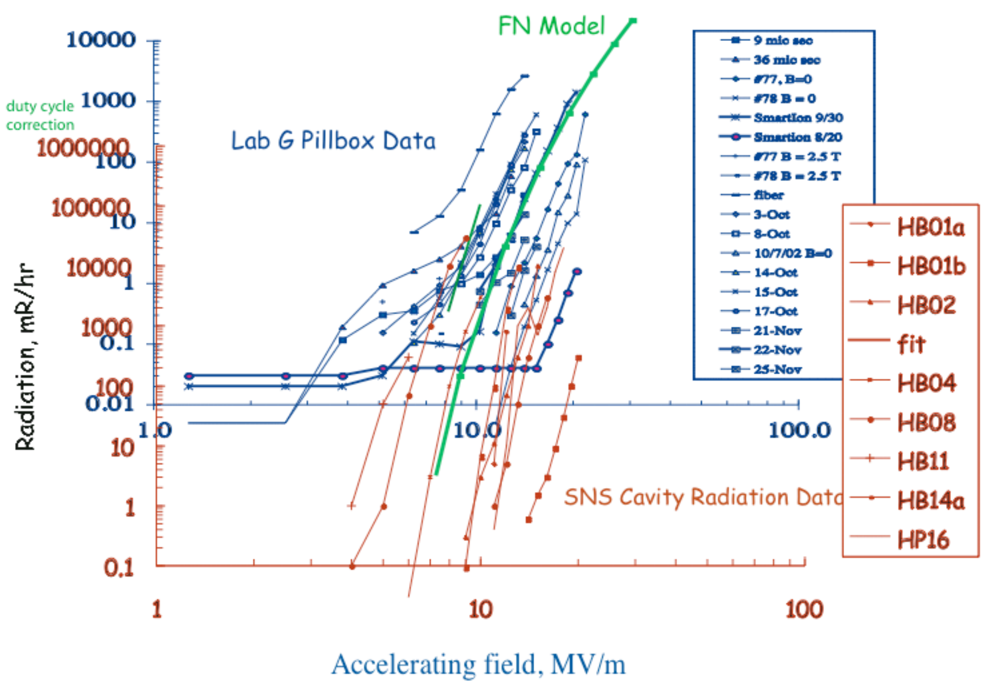
Using the model: XIII) High Solenoidal fields

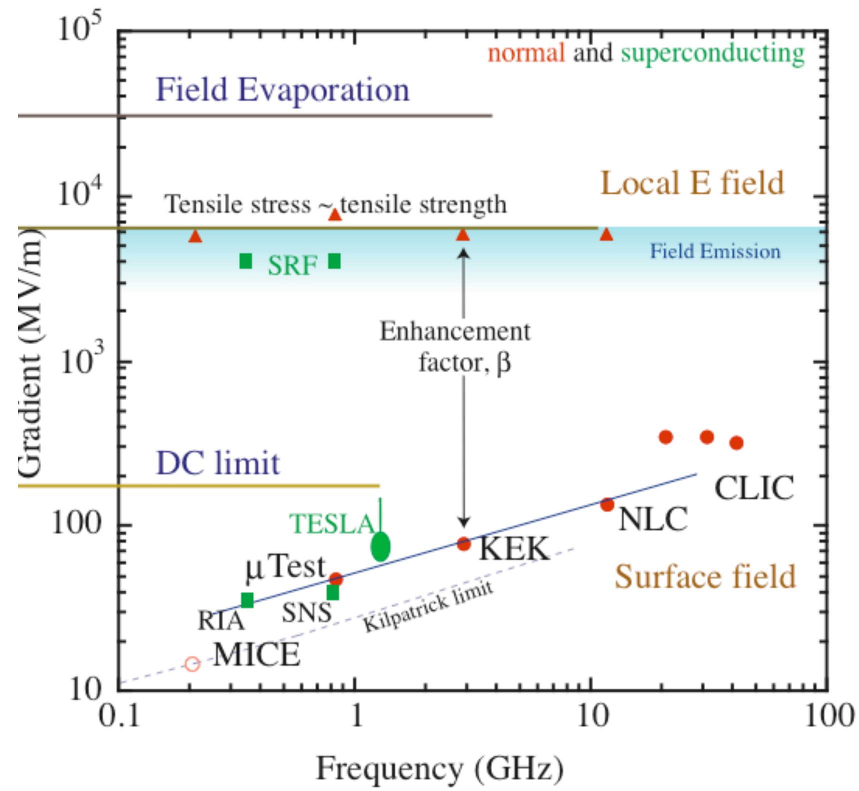
- This behavior is consistent with mechanical stress causing breakdown
- The geometry of the cavity seems to matter.
- Other effects (magnetic confinement of damage) may contribute.



Using the model: XIV) Superconducing rf

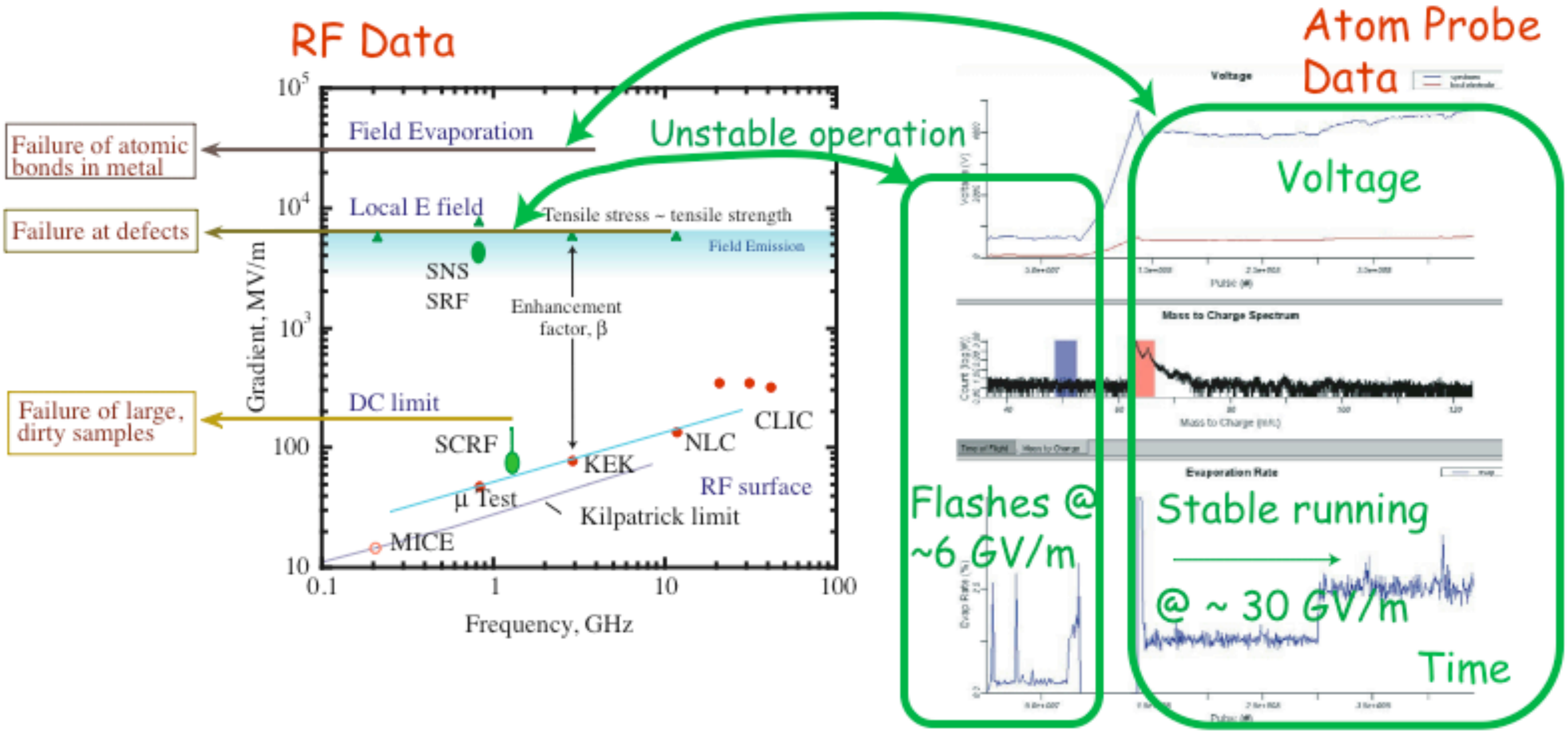
- For SCRF Emax = (4 GV/m)/ β, NCRF Emax = (7 GV/m)/ β
- Radiation levels, show SCRF for SNS has similar problems to NCRF.





Using the model: XV) Atom Probe Measurements

- Atom probe measurements show sample failure at approximately 7 GV/m.



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Conclusions

- High Gradient research (high and low frequency, normal and SC) is one field.
- Breakdown should be a science, not an engineering limitation.
- There should be a broad examination of field limiting phenomena.
  It should be possible to estimate limits with some precision.
- We have a model, which should be tested and made more precise.
- The model <u>seems to explain all aspects of breakdown phenomena</u>.
- The community needs a solution to this problem.